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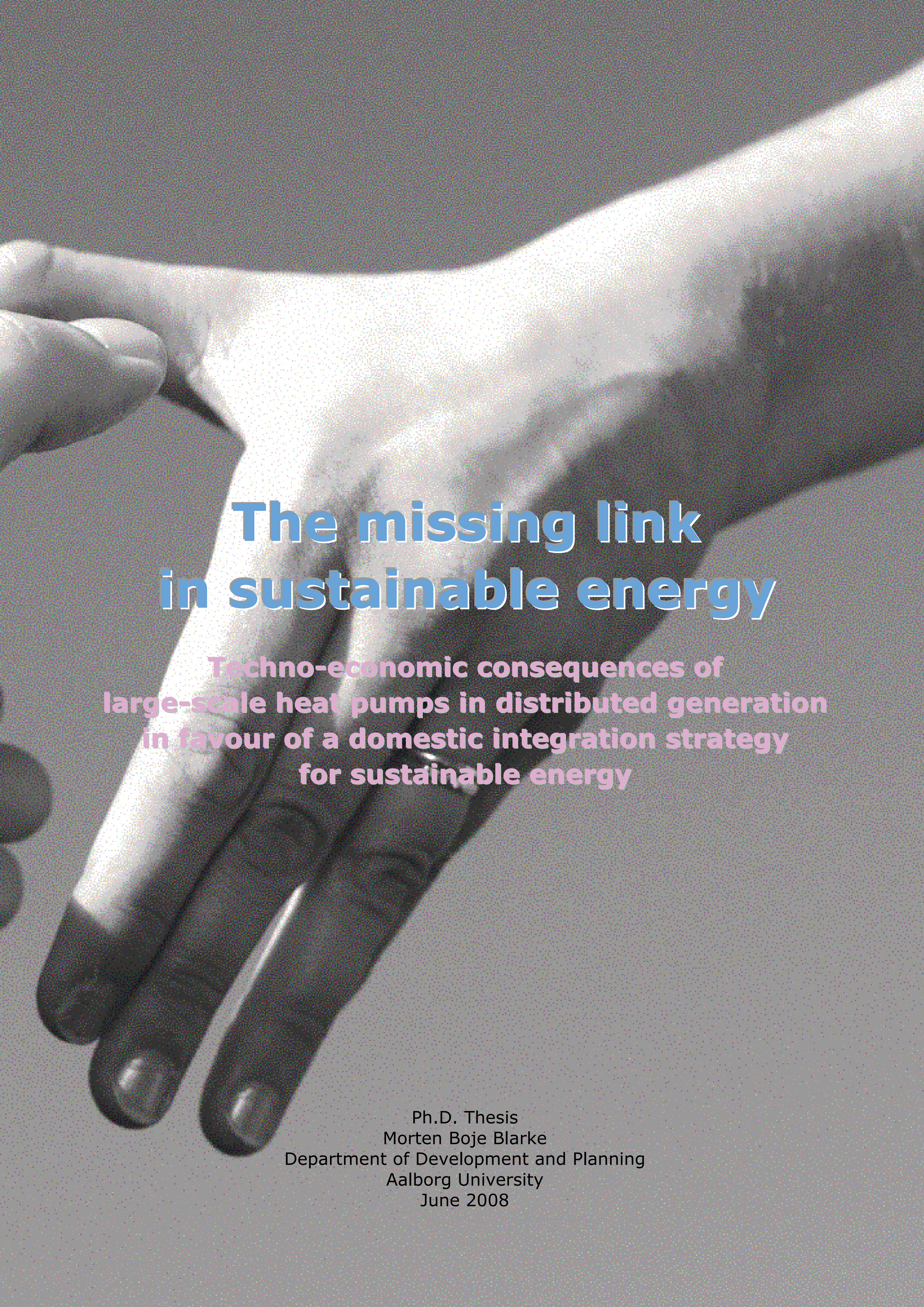

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Ph.D. Thesis

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Abstract

This thesis investigates options for handling the problem of intermittency related to large-scale penetration of wind power into the West Danish energy system. But rather than being a story about wind power, the thesis explores the principles by which distributed energy plants could be better designed and operated to provide energy system services, supporting intermittent supply, while reducing the need for central power plants and cross-national transmission capacities.

In essence, the thesis assesses the consequences of integrating large-scale heat pumps with distributed cogenerators in favour of a domestic integration strategy for handling intermittency towards a sustainable energy system.

It is found that large-scale transcritical compression heat pumps are suitable and ready for integration with existing cogenerators, but that system-wide energy, environmental, and economic benefits are very sensitive to actual concepts of integration. The innovative CHP-HP-CS concept that relies on heat recovered from cooling and condensation of flue gasses, adds, in addition to a heat pump, a cold storage for storing recovered heat, which allows for independent operation of cogenerator and heat pump. While this concept results in increasing a typical plant's fuel efficiency from 92 % to 97 %, the plant's reduced electricity production results in plant-related system-wide CO2 emissions increasing by as much as 20 %. The increase in CO2 emissions is minimized by disallowing concurrent operation of cogenerator unit and heat pump unit. The CHP-HP-GS concept that relies on unconstrained heat recovered from ground sources offers a 10 % reduction in the plant's system-wide CO2 emissions when disallowing concurrent operation.

The thesis shows that concepts for integrating heat pumps with cogenerators comes with significant variations in boiler operation and cogeneration being substituted, with the heat pump entering as an intermediate-load heat production unit with full-load hours as few as 1350 hours according to concept, and that the resulting overall economic costs of heat production typically increases by 2 % to 8 %. However, the thesis claims that increased costs may be acceptable as these concepts will reduce the need for investments in cross-national infrastructure.

The most cost-effective concepts for increasing the wind-friendliness of existing distributed generators relies on installing a relatively small heat pump, limiting the electric capacity of the heat pump to no more than 10 % of the electricity generating capacity of the distributed generator.

The most cost-effective heat pump concepts are more cost-effective than concepts for integrating an electric boiler.

The thesis provides new metrics, like the relocation coefficient, for evaluating the wind-friendliness of distributed generators, and the cost-effectiveness hereof, and offers a new interactive modelling framework that allows for researchers and local operators to interact on evaluating options for domestic integration with respect to energy, environmental, and economic consequences.

Keywords: sustainable energy system design, intermittency, large-scale heat pumps, distributed cogeneration, cold storage, relocation, domestic integration of wind power, interactive techno-economic modelling software.

Resumé

Denne afhandling undersøger muligheder for at håndtere problemet med diskontinuerlig energiproduktion som følge af vindkraftens høje andel af Vestdanmarks energiproduktion. Men snarere end at handle om vindkraft, udforsker afhandlingen principper efter hvilke decentrale energianlæg kan designes og opereres for bedre at yde systemtjenester, understøtte diskontinuerlig energiproduktion, og derved reducere behovet for centrale kraftværker og tvær-national transmissionskapacitet.

I sin centrale del, gennemfører afhandlingen en vurdering af konsekvenserne ved at integrere store varmepumper med decentrale kraftvarmeanlæg til fordel for en strategi for indenlandsk integration af diskontinuerlig produktion med henblik på etablering af et bæredygtigt energisystem.

Afhandlingen finder, at store transkritiske kompressionsvarmepumper er egnede og klar til integration med eksisterende kraftvarmeanlæg, men at de energi- og miljømæssige, samt økonomiske fordele, i et systemperspektiv er særdeles følsomme overfor de konkrete anlægskoncepter for integration. Det innovative CHP-HP-CS koncept, der er baseret på udnyttelse af varme genindvundet fra køling og kondensering af røggas, tilføjer, udover varmepumpen, et koldt varmelager, der muliggør lagring af denne lavtemperaturvarme, hvilket muliggør uafhængig drift af kraftvarmeenhed og varmepumpe. Alt imens dette koncept øger anlæggets totalvirkningsgrad fra 92 % til 97 % fører anlæggets reducerede elproduktion til, at anlæggets CO_2 emissioner i et system perspektiv øges med helt op til 20 %. Denne forøgelse af CO_2 emissionerne kan minimeres ved at undgå samtidig drift af kraftvarmeenhed og varmepumpe. CHP-HP-GS konceptet, der er baseret på jordvarmeoptag, reducerer anlæggets CO_2 emissioner i et systemperspektiv med 10 %, når samtidig produktion på kraftvarmeenhed og varmepumpe undgås.

Afhandlingen viser, at de undersøgte koncepter for integration af varmepumper afstedkommer væsentlige variationer med hensyn til i hvilken grad drift af kedel og kraftvarmeenhed substitueres, og at varmepumpen må forventes at indgå som dellastenhed med helt ned til 1350 fuldlasttimer afhængig af koncept. De resulterende samfundsøkonomiske varmeproduktionsomkostninger øges typisk med 2 % to 8 %, men afhandlingen hævder, at en generel omkostningsforøgelse kan være acceptabel, da koncepterne reducerer behovet for investeringer i tvær-national infrastruktur.

Højeste omkostningseffektivitet opnås ved at installere en relativ lille varmepumpe med en elforbrugskapacitet på mindre end 10 % af den decentrale kraftvarmeenheds elproduktionskapacitet. De mest omkostningseffektive varmepumpekoncepter er mere omkostningseffektive end koncepter for integration af elkedler.

Afhandlingen har udviklet ny metrik, herunder relokeringskoefficienten, for at vurdere decentrale anlægs vindvenlighed, og omkostningseffektivitet, og tilbyder et nyt interaktivt modelværktøj, der gør det muligt for forskere og lokale operatører af energianlæg at interagere om muligheder for at øge et anlægs vindvenlighed, herunder at vurdere forandringens energi- og miljømæssige, samt økonomiske konsekvenser.

Nøgleord: design af bæredygtige energisystemer, diskontinuerlig energiproduktion, store varmepumper, decentral kraftvarmeproduktion, koldt varmelager, relokering, indenlandsk integration, interaktive teknisk-økonomiske modelværktøjer.

Kort resumé: Afhandlingen udforsker koncepter efter hvilke decentrale energianlæg kan designes og opereres for bedre at understøtte diskontinuerlig energiproduktion, f.eks. vindkraft, og derved reducere behovet for centrale kraftværker og tvær-national transmissionskapacitet. En række teknisk-økonomiske analyser af varmepumper og elkedler i Vestdanmarks decentrale kraftvarmeproduktion dokumenterer hvordan sådanne ændringer vil gøre værkerne mere ”vindvenlige”, og indgår i en vurdering af, at sådanne løsninger er omkostningseffektive, når de kan fortrænge investeringer i elnettets udvidelse.

Publications

Primary publications

I. Blarke, M B and Lund, H (2007). 'Large-Scale Heat Pumps In Sustainable Energy Systems: System And Project Perspectives', Journal of Thermal Science 11 (3) 141-152.

II. Blarke, M B and Lund, H (2008). 'The effectiveness of storage and relocation options in renewable energy systems', Renewable Energy 33 (7) 1499-1507.

III. Blarke, M B (2007). 'Interactivity in Planning: Frameworking Tools' in Kørnøv L., Thrane M., Remmen A. and Lund H. (eds) Tools for Sustainable Development Aalborg, Aalborg Universitetsforlag.

IV. Blarke, M B and Andersen, A (forthcoming). 'Technical and economic effectiveness of large-scale compression heat pumps and electric boilers in energy systems with high penetration levels of wind power and CHP', submitted for publication to Energy – The International Journal in April 2007. Status: Under review.

V. Blarke, M B (forthcoming). 'Energy system analysis of large-scale heat pumps and other relocation options', submitted for publication to Energy – The International Journal in September 2007. Status: Under review.

VI. Blarke, Morten Boje. 'Large-scale heat pumps in sustainable energy systems' in Long-term perspectives for balancing fluctuating renewable energy sources 83-92. 1-3-2007. DESIRE report.

VII. Blarke, Morten Boje. 'From dusk till dawn: An essay about how the climate crisis has come to define sustainable energy in the context of the Danish experiment'. 23-5-2008. Essay published with this thesis.

VIII. Blarke, Morten Boje. COMPOSE: Compare Options for Sustainable Energy. [1.0]. 23-5-2008. Computer program released with this thesis.

IX. Blarke, Morten Boje. EnergyInteractive.NET. 23-5-2008. Computer program released with this thesis.

Secondary publications

X. Blarke, Morten Boje. 'District Heating Plant Operators Foresees A Future With Electric Boilers' (In Danish: Fjernvarmeværker forventer fremtid med elpatroner - Nu kommer den helt forureningsfri fjernvarme - men er elpatroner vejen til verdens reneste og mest effektive energisystem?). Fjernvarmen [6/7], 24-26. 1-6-2006. Kolding, Denmark, The Danish District Heating Association. Magazine Article.

XI. Blarke, Morten Boje. 'Interactive energy planning: Towards a sound and effective planning praxis', World Renewable Energy Congress IX. Proceedings of World Renewable Energy Congress IX. 1-8-2006. Conference Proceeding.

XII. Blarke, Morten Boje. 'Large-scale heat pumps with cold storage for integration with existing cogenerators' (In Danish: Store varmepumper med koldt varmelager i forbindelse med eksisterende kraftvarmeproduktion), in The Danish Society of Engineers' Energy Plan 2030. 1-12-2006. Background report.

XIII. Blarke, Morten Boje. 'Techno-economic Assessment of CHP-HP concepts for Dronninglund District Heating' (In Danish: Teknisk-økonomisk vurdering af kraftvarmepumpe-koncept til Dronninglund Fjernvarme A.m.b.A.). 1-10-2006. Report.

XIV. Blarke, Morten Boje. 'Let's future-proof distributed cogeneration' (In Danish: Lad os fremtidssikre den decentrale kraftvarme-produktion). Ingeniøren [34]. 24-8-2007. Feature Article

XV. Blarke, Morten Boje. 'A minor adjustment of taxation rates could mean a breakthrough for large-scale heat pumps, more efficient cogeneration, and the integration of wind power' (Danish: En lille justering af afgiftsreglerne kunne blive et gennembrud for de store varmepumper, mere effektiv kraft-varmeproduktion, og indregulering af vindkraft). Ingeniøren. 4-8-2006. Feature Article

Contribution of the author to papers with co-writers

Paper I, II, and IV were all developed and written by Blarke with co-writers providing comments in the process, and with the following specific contributions:

In Paper I, Lund's initial sketches for EnergyPLAN inspired Blarke to produce Figure 2.

In Paper II, as in Paper I, the evolving generational sustainable energy system design is basically a further development of Lund's initial energy system sketches for EnergyPLAN.

In Paper IV, Andersen developed the particular way cold storage is modelled as a constrained fuel in EnergyPRO for Blarke's analyses of the CHP-HP-CS concept.

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Nomenclature

CHP	Combined heat and power
CHP-EB	CHP plant with electric boiler
CHP-HP	CHP plant with heat pump
CHP-HP-CS	CHP plant with heat pump and cold storage
CHP-HP-GS	CHP plant with ground source heat pump
COP	Coefficient of performance
CS	Cold storage
EB	Electric boiler
HP	Heat pump
IRR	Economic internal rate of return
kWe, MWe	Electric capacity
O&M	Operation and maintenance costs excluding fuel costs
Rc	Relocation coefficient
€ 1	DKK 7,45
TSO	Transmission System Operator
Mt	Million tons
JI	Joint Implementation
CDM	Clean Development Mechanism
Cm	Power to heat output ratio
T&H	Transportation and handling
L1417	Law 1417/2005

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1. Introduction

The essay "From dusk till dawn" published with this thesis, argues that any research into the Danish energy system should be put into perspective of both the climate crisis, the Danish energy system as an experiment of global interest, as well as the conflicting interests at play in defining strategies for sustainable energy [1].

With respect to the climate crisis, Denmark has taken substantial steps, in particular since 1985 [1], towards obtaining what is now the second lowest CO2 footprint among non-nuclear energy systems. But there is little reason to celebrate an intensity figure of 284 grams of CO2 per kWh[1], because in terms of total emissions, Denmark is far off target. In 2007, CO2 emissions are 13 % lower than in 1990, while Denmark is committed by EU quota sharing agreements to a 21 % reduction in CO2 emissions by 2012. The EU agreement requires for Denmark to emit no more than 54,8 Mt annually during 2008-2012, but the national CO2 allocation plan approved by the European Commission in March 2007, projects that emissions are more likely to reach 68 Mt annually [2]. According to Energinet.dk's 2007 Environmental Report [3], CO2 emissions from central electricity and heat supply totalled 25,8 Mt in 2006, which in the context of the allocation plan for 2008-2012 would then represent about 30 % of total emissions.

The problem was, and is, how to reduce CO2 emissions by an additional 13 Mt annually towards 2012. This involves identifying energy sector options that would contribute in this respect, while settling the criteria by which candidate options for doing so are evaluated.

According to the national allocation plan, the objective is for 72 % of the 13 Mt deficit to be found by emissions trading and JI/CDM credits, while only a 3,6 Mt reduction is deemed feasibly achievable by additional domestic measures. The key argument for prioritizing carbon trading over domestic measures is economic cost-effectiveness. Back in 2003, the Ministry of Finance arrived at the conclusion that the deficit, which at

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[1] Found when totaling emissions from fossil fuels consumed by power plants, cogeneration plants, and boilers and dividing by the output of electricity and heat generated.

that point was projected to be 25 Mt per year[2], could be avoided at an annual economic cost of between €135 mill. and €670 mill., lowest in a combination of 75 % trading and 25 % domestic measures, highest when only applying domestic measures [4]. In March 2008, this strategy is supported by the Environmental Economic Council, who also rejects the idea that the gap may be closed cost-effectively by setting specific technology targets as this is resulting in reduction costs, which are higher than trading markets are readily supporting [5].

In fact, cost-effective CO2 reduction may be the single most important operational climate policy objective, and consequently also a key objective against which the findings of this thesis will be evaluated. However, though obviously influential, climate and energy policy is not necessarily set by considerations of economic cost-effectiveness. In February 2008, despite the Environmental Economic Council's warnings, the Danish Folketing agreed on a number of domestic measures targeting the energy sector, which are intended to narrow the CO2 reduction gap [6]. The "Energy Policy Agreement of February 21, 2008" is establishing specific technology targets for replacing fossil fuels with renewables in heat and electricity supply. The objective is to reach 20 % renewables in energy supply by 2011, and 30 % by 2025, up from 16 % in 2007.[3] These targets are in line with Denmark's EU energy policy commitment to reach 27 % by 2020. A central technology target is the plan to increase the installed wind power capacity by 150 MW on-shore and 400 MW off-shore.

With a specific technology target in place, the question is no longer whether these measures represent a cost-effective response to the climate policy compared to trading, but rather how the energy system may cost-effectively accommodate an additional 550 MW of wind capacity by 2012, adding to those 750 MW already in the pipeline.[4]

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[2] With no correction for the unusual electricity import in 1990.

[3] Adjusted for climate conditions against normal year, as well as net electricity exports. Preliminary figures according the Danish Energy Authority (15/03/08).

[4] Rødsand II off-shore (200 MW), Horns Rev II off-shore (200 MW), and the scrapping measures (350 MW).

Projected to make up for 20% of the Danish electricity supply in 2008, even 25 % in the West Danish energy system, the increasing penetration levels for wind power presents a real challenge. In March 2007, Energinet.dk's projected the technical challenges associated with increasing the penetration rate of wind power toward 2025 to 51 % of final electricity demand (44 % of supply) within an energy system and market also affected by high penetration rates for distributed cogenerators [7]. In a reference alternative that includes already planned cross-national transmission capacities, critical excess electricity supply is projected to occur in 10 % of all hours, totalling 700 GWh, while net electricity exports increases to 8500 GWh.

How is this a problem? As described in [8], critical excess supply does not really occur, but its near-occurrence strongly influences electricity markets, driving spot prices down, thereby also driving down the specific electricity payments to wind producers. This could scare investors off, resulting in under-investments, which would jeopardize plans for large-scale penetration of wind power, undermining security of supply. As for increasing electricity exports, this involves exporting electricity over long distances, which increases grid losses, while requiring significant investments in grid infrastructure. Also, increasing exports of wind power represent an unreaped potential for reducing domestic fossil fuel based supply.

This thesis responds in particular to this challenge by researching the consequences, including the cost-effectiveness, of introducing options that would allow for supporting increasing levels of wind power into the domestic energy system.

In [7], Energinet.dk lists the main short-term options available for handling the intermittency challenge: increasing cross-national and intra-national transmission capacities, regulating wind turbines, introducing flexible electricity demand, storing electricity, and coupling heat and electricity supply. But how are such options best compared and evaluated with respect to important policy objectives, such as climate, energy, and economic cost-effectiveness?

The thesis will argue that it is not reasonable to compare options across the two major strategies for handling increasing penetrations levels of wind power: *domestic integration* and *open access*. And that these major strategies are mutually exclusive, at least over a foreseeable 20 year planning period.

A *domestic integration strategy* would involve investments in for example distributed generation to allow for greater operational flexibility of the domestic energy system.

An *open access strategy* would involve investments in increasing cross-national and intra-national transmission capacities to allow for increasing exports and imports of electricity.

It is envisioned that investments in an open access strategy would render investments in distributed generation and domestic integration ineffective. An open access strategy would furthermore open the Danish energy system towards competing technology paradigms for carbon-neutral energy, like nuclear power.

In reflection, the thesis hypothesizes that investing in options for domestic integration would strengthen the role of distributed producers, and strengthen Denmark as perhaps the only candidate on the global scene in a position that allows for evaluating whether a *domestic integration* strategy for sustainable energy is doable and feasible. In contrary, an open access strategy would weaken the role of distributed producers, and jeopardize Denmark's historically rooted praxis in sustainable energy, the perspectives of which are discussed in [1].

An underlying assumption for this hypothesis is that a domestic integration strategy is incompatible with an open access strategy over a foreseeable planning period, and that such incompatibility requires for decision-makers not just to initiate particular actions to promote domestic integration, but also to terminate plans that promotes open access. In view of the above, current plans for investing at least €400 mill. in increasing cross-border transmission capacities to Sweden and Germany is a threat to the continuation of the Danish experiment for domestic integration of sustainable energy. If this budget could be re-directed towards options for domestic integration, the amount matches the total investment required for implementing the innovative CHP-HP-CS concept, which is introduced and evaluated with this thesis, for all distributed cogenerators in Denmark. This would establish the flexibility of

150 MWe large-scale heat pumps in district heating production, significantly increasing the wind-friendliness of distributed cogeneration.

The thesis does not attempt any further comparisons across these mutually exclusive strategies for sustainable energy. Instead the thesis focuses on the development and application of methodologies and frameworking tools for comparing relocation options, such as the CHP-HP-CS concept, in support of a domestic integration strategy for handling intermittent resources.

2. The principle of relocation

The journal article "The effectiveness of storage and relocation options in renewable energy systems" published in "Renewable Energy" in July 2008 [9], introduces a new principle in sustainable energy system design, a principle for which my colleagues and I have chosen the term "relocation". In the article, relocation is defined as the principle of coupling energy carriers, and it is suggested that the introduction of the principle of relocation is a fundamental energy system innovation that identifies the transformation from a first to a second generation sustainable energy system. In support of this hypothesis, the article analyzes the basic system design and operational principles by which storage and relocation technologies may better allow for domestic integration of intermittent renewable energy resources and cogeneration.

Figure 1 illustrates that the transition from a pre-sustainability energy system to a 1G sustainable energy system is signified by the introduction of two major components: cogeneration of heat and power, and intermittent renewable resources. As penetration rates of these components increase, so does the need for increasing system flexibility. The transition from a 1G to a 2G sustainable energy system is signified by the introduction of the principle of relocation, which allows for distributed cogenerators further to reduce the need for power-only and heat-only plants, as cogenerators now provides the required flexibility to support intermittency.

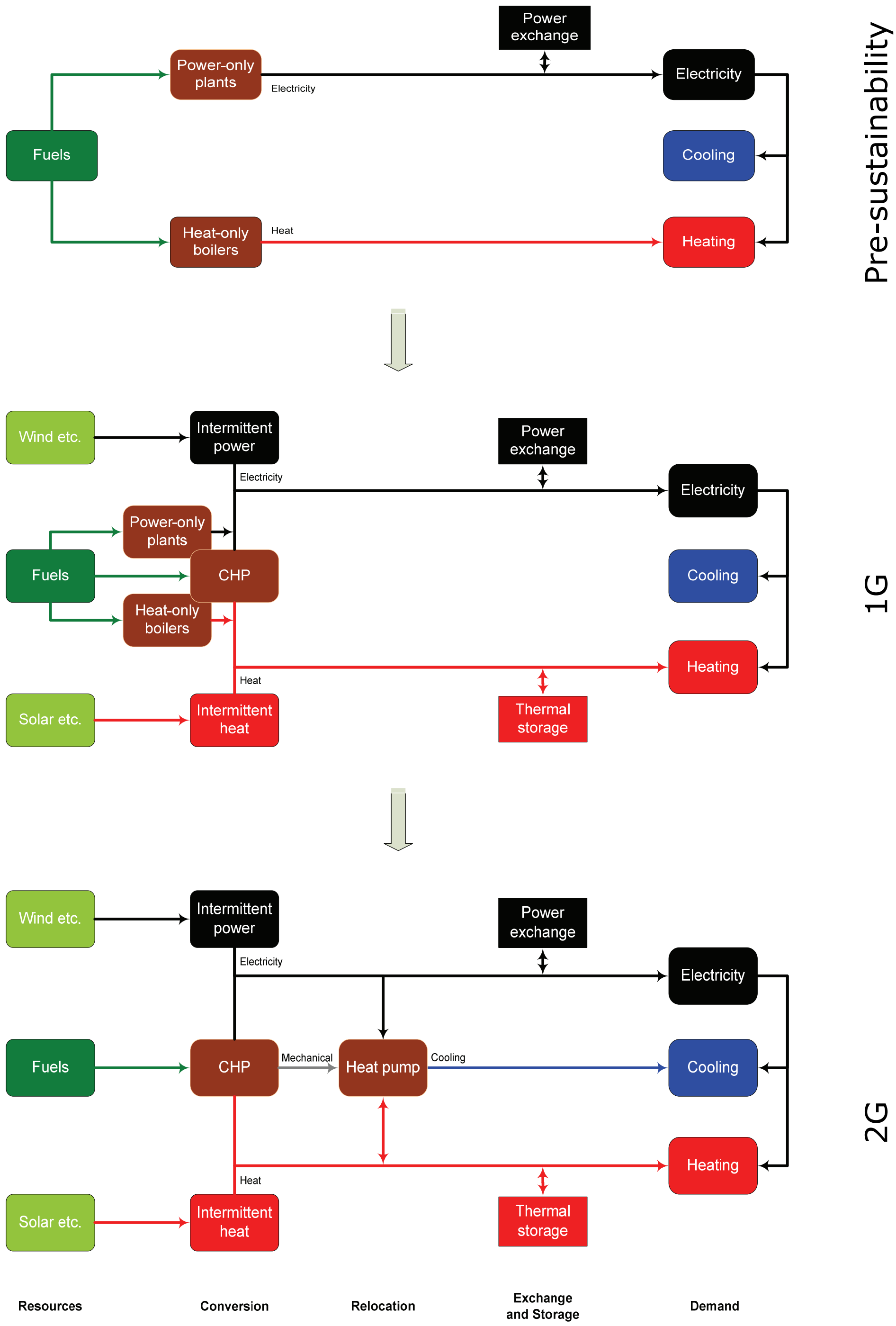

Figure 1: Transition from pre-sustainability energy system, to first and second generation energy systems, introducing relocation as the missing link in the design of sustainable energy systems. Transportation is excluded from this illustration.

Is the principle of relocation *the missing link* in the evolution of sustainable energy systems? And to which degree does distributed cogenerators support intermittency, and is it at all possible for distributed cogenerators completely to replace central power-only plants?

The article introduces a new metric, *the relocation coefficient (Rc)*, to support a comparative assessment of the intermittency-friendliness (or wind-friendliness) of relocation options. The relocation coefficient is defined as the statistical correlation between net electricity exchange between plant and grid, and the electricity demand minus intermittent renewable electricity production (Equation 1).

$$R_c = \frac{\sum (e - e_m)(d - d_m)}{\sqrt{\sum (e - e_m)^2 \sum (d - d_m)^2}}$$ **Equation 1**

By comparing options, for which the operational strategy is known on an hourly basis with respect to net electricity exchange with the grid, by their relocation coefficient, we arrive at a simple, yet telling measure that provides insight into how well an option is supporting fluctuations in electricity demand and intermittent electricity supply within a given system. A relocation coefficient of 1 illustrates that an option is perfectly in sync with the requirements of a given energy system, which may then in principle be operated alone on the basis of this particular option. For example, if a 1 MWe CHP plant with a 1 MWe heat pump satisfying a given heat and cooling demand, which is operated in an energy system where the peak electricity demand is 1 MWe and the installed intermittent peak capacity is 1 MWe, can be operated to reach a relocation coefficient of 1, we arrive at a representation of an energy system that may be operated without any supplemental supply capacity, like central power plants or import/export exchange capacity.

The relocation coefficient is a useful measure for investigating how changing the operational strategy of a distributed plant, for example by integrating heat pumps or electric boilers, changes the ability of the plant to support intermittency.

Statistical analyses of how spot market prices are influenced by large-scale penetration of distributed cogeneration and wind power in the West Danish energy system, shows that the theoretical maximum relocation coefficient for a CHP plant operating on the basis of perfect navigation in a market assumed to reflect actual economic costs, including externalities, is 0,68, which basically reflects the historical statistical correlation between hourly spot market prices and electricity demand minus wind production. In other words, under the regime of the current spot market, and the costs internalized herein, a relocation coefficient of 0,68 represents an upper ceiling for how “wind-friendly” a distributed plant may be if operated cost-effectively.

By integrating storage and relocation technologies with distributed generators, the production profile for cost-effective operation for the distributed plant should increase. By comparing options by their relocation coefficient, we are able to quantify this as an increase in “wind-friendliness”.

The articles furthermore defines a economic shadow cost of relocation, defined as the economic costs for increasing the relocation coefficient by 1%-point, thereby introducing a measure for the cost-effectiveness of increasing wind-friendliness (Equation 2).

$$P_{Rc} = \frac{\sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{\Delta Rc_t}{(1+r)^t}} \quad \textbf{Equation 2}$$

The article “Technical and economic effectiveness of large-scale compression heat pumps and electric boilers in energy systems with high penetration levels of wind power and CHP” submitted for publication to Energy in April 2007 [10], and summarized later, presents an operational modelling framework for comparing relocation options including the use of these new comparative metrics. The analysis compares 6 relocation technology options, initially finding that current operational practices in distributed generation lie much below the upper ceiling for wind-friendliness established above.

But what is a relocation technology, and which relocation concepts are relevant for inclusion in comparative analyses?

3. Relocation technology

The thesis will claim the existence of only two basic relocation technologies that couples electricity and heat: electric boilers and compression heat pumps.

An electric boiler, or resistance heater, is the simplest approach to relocation. At an investment cost of about €100,000 per MWe for integration with an existing cogeneration plant, and a conversion efficiency of almost 100%, excluding conversion losses in electricity production, the electric boiler is a straight-forward option for coupling energy carriers electricity and hot water, or hot air. However, an electric boiler does not allow for producing cooling.

Six different heat pump principles are evaluated with respect to the ability for providing relocation in an article published as Chapter 6 of the scientific report "Long-term perspectives for balancing fluctuating renewable energy sources" [11] published in March 2007. The article arrives at the conclusion that a compression heat pump appears to be the ideal relocation technology. However, at investment costs for integration with an existing cogeneration plant varying according to concept from €1,5 mill. to €3,5 mill. per MWe, careful conceptual considerations are required for heat pump to provide cost-effective relocation.

4. Large-scale heat pump applications

In [11], the principle by which a compression heat pump may be the ideal relocation technology is confirmed, but the evaluation of past and current applications for large-scale compression heat pumps relay a number of issues that needs to be considered in any future application of large-scale compression heat pumps.

The article evaluates three large-scale compression heat pump applications, including the 10 MWq heat pump established in Frederikshavn, Denmark, in 1980, the world's largest at the time, the 0,5 MWq heat pump installed in Ronneby Municipality, Sweden, also established in 1980, as well as the world's currently largest compression heat pump in district heating located in Umeå, Sweden, which has been in operation since September 2000.

One general conclusion is that large-scale compression heat pumps for district heating are not an off-the-shelf turn-key solution, but rather a customized industrial component. This partly explains the relatively high costs of investment. There are several reasons for the customized nature of large-scale heat pump applications, but one particular important reason is the need for establishing a low-temperature heat source or cooling demand, like heat recovered from flue gasses, ground or rock-source, solar, sea, lake, waste water, ambient air, intercooling, or a cooling demand. Clearly, the availability of a low-temperature heat source is a localized matter, and the availability and temperature level of this heat source guides not only the resulting COP, but the entire operational design of the heat pump, including the sizing and construct of heat exchangers.

Another conclusion is that none of the studied past or existing heat pump applications would fit the purpose of relocation within a 2G sustainable energy system. Either they are mechanically powered without providing any significant flexibility, or they are integrated with other production units that requires for concurrent operation of all units, or they are designed for base load operation with a high number of full-load hours.

Another conclusion is that the temperature level at which it is possible for heat to be delivered can be a problem for stand-alone operation. In Ronneby, no supplemental heating supply was provided in a low-temperature design that was supplying district heating at 60°C. Ultimately, this did not satisfy consumers, and may help explain why the heat pump was replaced by a wood-fired boiler in 1993. In fact, for known applications, temperature levels above 70°C are unusual, and are typically requiring for the compression to take place in multiple steps. For common industrial large-scale working fluids, like ammonia (NH_3) or HFCs (like R134a), reaching temperatures levels between 70°C and 75°C results in either very low COPs, or very complex machinery.

Finally, it is concluded that the potential threats from using particular working fluids was a critical issue in decisions to discontinue early plants. The heat pumps in Frederikshavn and Ronneby were using the most aggressive ozone depletion and global warming potent working liquids R114 and R12 in complex mechanical systems. In fact, Frederikshavn had particular problems with leaking sealings, and in 1987 this was a supporting argument for replacing the heat pump with a natural-gas fired cogeneration plant [12]. In Umeå, the world's currently largest heat pump in district heating uses R132a for working liquid, which generally has replaced R12 in the industry since the early 1990's. However, while R132a does not contribute to ozone depletion, the gas has a global warming potential of 1300, and restrictions for use of R132a are being introducing on several fronts.

The problems relayed in this review of past and current experiences with large-scale heat pump applications suggest the need for technological innovations with respect to standardization of the application of large-scale heat pumps, higher delivery temperature levels at high COPs, non-hazardous working liquids, and the introduction of support for relocation.

5. Baseline survey provides clues

The feature article "District Heating Plant Operators Foresees A Future With Electric Boilers" published in June 2006 [13] presents the results of a survey carried out among existing operators in district heating about their plans, attitude, and techno-economic expectations towards using electricity for district heating production.

On the basis of 60 respondees, the survey finds that only 12 % of the respondees considered it likely or very likely that they would have a large-scale heat pump in production within 3-5 year, while 27% considered it likely that they would have an electric boiler in operation within this period.

However, the survey also finds that almost half of the operators are generally very keen for a chance to experiment with large-scale heat pumps, being willing to host a demonstration project, but while some are sceptical towards the potential economic benefits, 58 % of the respondees state that they have no knowledge about the economic consequences of integrating a large-scale heat pump.

As for local availability of low-temperature heat sources, most notably only 16 % suggested ground source heat, while 40 %

pointed to solar heating as a potential source. However, almost 60 % pointed to flue gas condensation or intercooling for an available low-temperature heat source. The survey shows that the local availability of a low-temperature heat source varies from place to place, but that operators are generally supportive of a solution that integrates heat pumps with the existing plant, thereby also possibly increasing the plant's overall fuel efficiency by utilizing heat recovered from existing processes.

6. The CHP-HP-CS concept: Innovative relocation

In the spring of 2006, an R&D effort by the Danish Technology Institute in relation to transcritical CO2 heat pump (HP) technology allowed for a group of partners to get together for what was intended to be a full-scale demonstration project of a mechanically powered HP with a natural gas engine that utilizes heat recovered from flue gasses.

By focusing on the utilization of heat recovered from flue gasses as an internal low-temperature heat source, this concept offers a solution that does not depend on the identification of external localized low-temperature heat sources. And by the application of a transcritical cycle that uses CO2 as the working liquid, the technology rids itself of previous problems related to poisonous, ozone depleting, and global warming potent working liquids.[5] With CO2, the HP unit reaches compressor discharge pressure levels of up to 115 bar, which allows for exit temperatures of 80°C at a design COP as high as 3,8, periodically up to 90°C with only little influence on the COP [14]. This exit temperature level makes the concept suitable for district heating grid delivery or production for thermal storage. The concept thereby solves a number of the key problems related to previously.

However, Aalborg University made it evident to the group that only an electrically powered HP unit would potentially be

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[5] It is noted that such a system would hold about 30 kg of CO2 for a 1 MWq heat pump, which corresponds to the global warming potential of 1/1300 of a similarly sized heat pump on using a typical R132a upon accidential release to the atmosphere.

supportive of the principle of relocation, thus supporting a 2G sustainable energy system.

In order to allow for an electrically powered HP unit to operate without concurrent operation of the CHP unit, which is required for providing relocation, while still utilizing heat recovered from flue gasses, the group then came up with an innovative, yet simple solution: the cold storage (CS).

The CS stores low-temperature heat recovered from low-pressure cooling and condensation of flue gasses whenever the CHP unit is in operation. When the HP unit then operates, it utilizes this heat as a low-temperature heat source, thus generating cold water for subsequent low-pressure cooling and condensing of flue gasses. As such, the CS is operated as an integrated low-temperature heat source, allowing for high-efficiency operation of the heat pump without concurrent operation of the CHP unit. The CHP unit and the HP unit may however also be operated concurrently.

The capacity of the HP unit is designed under constraint of the heat available for recovery from cooling and condensation of flue gasses. For a typical distributed cogenerator, this allows for the installation of a HP unit no larger than 10% of the installed electric capacity, thereby increasing the plant's heat production capacity by about 20% depending on Cm-values. The CS temperature levels will typically be ranging from 10-20°C in the bottom to 50-60°C in the top.

In December 2006, the Danish Technology Institute and partners, including Aalborg University, was awarded €1,5 mill. for a full-scale demonstration project and further research into the CHP-HP-CS concept.

Figure 2 illustrates the CHP-HP-CS concept together with other relevant relocation concepts, which have been included with various comparative techno-economic investigations included with this thesis.

The CHP-HP concept adds an electrical (Option A) or mechanical (Option A Alternative) HP unit that uses flue gas cooling as the only low-temperature heat source. The CHP-HP-CS concept, which has been analyzed for both concurrent (Option B) and non-concurrent operation (Option C) of production units, adds a cold storage in addition hereto, allowing for constrained independent operation of CHP unit and HP unit. The CHP-HP-GS concept adds a HP unit as well as a ground source heat exchanger, allowing for operating the HP unit independently of the CHP unit. The CHP-HP-GS concept has been analyzed for various HP unit capacities ranging from having an electric capacity similar to that of CHP-HP-CS (Option D) to a heat production capacity similar to that of the CHP unit (Option E). Finally, the CHP-EB concept adds an electric boiler (EB) with a heat production capacity similar to the CHP unit (Option F).

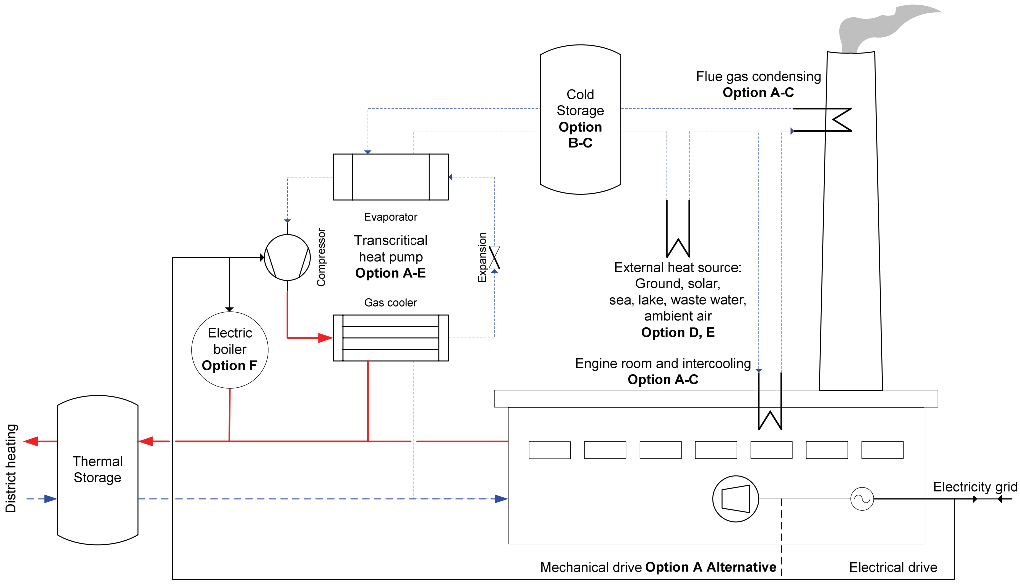

Figure 2: Combined illustration of the CHP-HP, CHP-HP-CS, CHP-HP-GS and CHP-EB concepts under analysis in [10].

Key relocation concepts under investigation						
Reference	**A**	**B**	**C**	**D**	**E**	**F**
CHP	CHP-HP	CHP-HP-CS	CHP-HP-CS	CHP-HP-GS Lim	CHP-HP-GS Full	CHP-EB Full
Concurrency allowed			Concurrency disallowed			

The effort to assess the comparative energy, environmental and economic consequences of these options for relocation, has involved techno-economic plant design and operational analyses, energy system analyses, and the development of a project-system hybrid methodology and modelling tool.

7. Methodologies and tools in techno-economics

The article "Energy system analysis of large-scale heat pumps" submitted for publication to Energy in September 2007 [15] investigates how relocation options may be evaluated with respect to the interaction between energy, economy, and environment.

The article suggests the existence of four complementary methodological dimensions for modelling the interactions between energy, economy and environment: top-down versus bottom-up, and macro-economic versus techno-economic.

The thesis approaches the evaluation problem from a techno-economic perspective, which basically considers the energy sector in greater technical detail, the results being engineered by user-specified technological changes, using mainly exogenous assumptions for future techno-economic characteristics.

The thesis does not include any macro-economic system analysis of introducing large-scale heat pumps into the energy system. While a macro-economic top-down approach would have described the energy system in an aggregated way and as a sub-sector of the entire economy, the results being induced by relative price changes, the thesis does for example not attempt to evaluate any economy-wide lost opportunity costs from increasing investments in this technology area. In reflection, the current methods available in macro-economic analysis for introducing energy system changes would hardly have allowed for evaluating the consequences of such specific technological innovations. Such consequences are currently best evaluated in techno-economic models of the energy system.

But also in techno-economic modelling, the top-down and bottom-up dimensions may be said to co-exist in the form of energy system and energy project models, and a key methodological challenge has been to combine the strengths of these approaches in the evaluation of the identified relevant options for relocation.

The thesis has applied widely-recognized system analysis and project operational design modelling tools in the evaluation of options, mainly EnergyPLAN [16], SIVAEL [17], and energyPRO [18], while also having developed and applied the new hybrid energy system-project model COMPOSE, released with this thesis, and described in more detail later.

EnergyPLAN and SIVAEL are system models that attempt to represent the Danish energy system with respect to heat and electricity supply and demand, with some level of aggregation, while energyPRO is a project operational design model that models a single plant with respect to demands and production units under given detailed techno-economic constraints. All three models may be used to optimize the operation of an energy system, or energy project, according to least economic costs.

COMPOSE is intended to be a hybrid model that integrates the strength of the system-wide perspective of EnergyPLAN with the detailed operational characteristics arriving from energyPRO.

All models rest on applying exogenous assumptions for future techno-economic characteristics, only EnergyPLAN includes an electricity market feed-back model that is applied endogenously to allow variations in supply and demand to influence electricity spot markets.

8. Consequences of simple relocation concepts

In [15], the thesis applies SIVAEL and EnergyPLAN in constructing energy system scenarios for 2010 subject to common assumptions derived from the Danish Energy Agency's assessment of consequences of the agreed energy conservation agreement of June 2005 [19]. The article presents a partial evaluation of the energy, environmental, and economic consequences of introducing 28 MWe (100 MWq) large-scale heat pumps with a COP of 3,5 into district heating in an energy system only incrementally different from today's system. Thereby the article establishes a partial and near-future energy system analysis of large-scale heat pumps; particularly exploring how these widely-recognised models for the Danish energy system accommodates the need to evaluate different concepts for integrating large-scale heat pumps into the energy system, and to investigate whether these models would reflect changes similarly. The article models only the demand and supply of electricity and district heating.

For both models, a least-cost approach is applied to the dispatching of plants according to the individual plant's (SIVAEL) or group of plants' (EnergyPLAN) short-term marginal costs of operation.

In addition to projected economic fuel costs, T&H costs, and O&M costs, the scenarios for 2010 are subject to economic shadow costs according to current energy and environmental taxation levels, as well as economic shadow costs for carbon credits. Applying these shadow costs, the models were used to simulate the consequences of changes in the energy system as assumingly operated under projected market conditions.[6]

Both models allowed for an alternative scenario that introduces an un-constrained HP or EB unit into district heating supplementing existing CHP unit and boiler operation. In SIVAEL, the HP unit is introduced into the Aarhus district heating area, while in EnergyPLAN, the HP unit is introduced into one of two aggregate district heating areas.

However, neither SIVAEL nor EnergyPLAN allowed for analyzing the CHP-HP-CS concept, or any other concept that implies any constraints on the availability of a low-temperature heat source. Nor did neither model allow for defining a constraint that would disallow concurrent operation of CHP unit and HP unit. The constraint to disallow concurrent operation is relevant for several reason, not at least because energy taxation law L1417 under which electricity used for district heating production enjoys reduced taxation levels when used by a CHP plant, but only if the CHP unit is not concurrently operated. L1417 is discussed in further detail later.

Initially, it is found that even on the basis of reasonably similar assumptions, SIVAEL and EnergyPLAN are suggesting quite different reference scenarios for 2010. Notably, SIVAEL arrives at net electricity exports that are 50 % higher than suggested by EnergyPLAN. Furthermore, SIVAEL is suggesting

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[6] However, economic results refer to economic costs and benefits, excluding fiscal costs and benefits.

for the share of coal in primary fuel consumption to be 60 %, with biomass making up 12 %, while EnergyPLAN arrives at 49 % and 19 % respectively. In result, SIVAEL finds for unadjusted CO2 emissions in 2010 to be 33,4 mill. ton, while EnergyPLAN arrives at 26,2 mill. ton. By comparison, the Danish Energy Agency projects for adjusted[7] CO2 emissions in electricity generation and district heating to be 21,3 mill. ton for 2010 [19]. Besides the impacts of adjusting emissions for weather conditions and electricity imports/exports, the Danish Energy Agency arrives at relatively lower coal consumption, substituted by gas and biomass.

In the reference scenarios, total operational economic costs including benefits of net electricity exports, but excluding any value of carbon credits as well as the depreciation of investments, amounts to €658 mill. in SIVAEL, and €1156 mill. in EnergyPLAN. One reason for this difference is the consequence of EnergyPLAN arriving at a relatively lower consumption of coal vis-à-vis a relatively higher consumption of biomass than SIVAEL. This contributes to relatively higher fuel costs in EnergyPLAN's reference scenario. Another reason is that SIVAEL applies hourly price projections for each of the export markets, while EnergyPLAN applies a common market rate for export markets based on the adjusted domestic market price. This contributes to lower export benefits in EnergyPLAN's reference scenario.

While these differences with respect to the reference scenarios for 2010 could have been adjusted by tweaking assumptions and adapting modelling methodologies, the exercise attempted to apply the models on common exogenous assumptions, while applying a model architecture and methodology similar to that used in recent studies that applies SIVAEL [7] and EnergyPLAN [21]. The differences in system representation relays a basic challenge in energy system analysis with respect to understanding and evaluating system model authenticity; however, rather than attempting a normative judgement with respect to how well these models represent the energy system, [15] is primarily focusing on how these models *per se*

[7] The Danish Government adjusts emissions on the basis of variations in weather conditions and electricity imports/exports. In an international perspective this method is problematic and not immediately accepted by UNFCCC [20].

evaluates alternative partial scenarios for HP units in district heating.

In the alternative scenarios it is found that the number of full-load hours for the HP unit is 508 hours in SIVAEL, and 1750 hours in EnergyPLAN. For EnergyPLAN, it is observed that the HP unit is dispatched over the aggregated proxy CHP unit for electricity spot market prices below €31,3 per MWh.

Despite these differences, SIVAEL and EnergyPLAN provide almost identical results with respect to consequences relative to the reference scenarios.

For the alternative scenarios, it is found that the introduction of 100 MWq heat pumps into the Danish energy system by 2010 results in primary fuel consumption being reduced by between 0,2 % to 0,3 %, net electricity exports being reduced by around 1,2 %, and operational economic costs, excluding any value of carbon credits as well as the depreciation of investments, being reduced by 0,3 %. With both models, the domestic CO2 emission reductions amount to 40000 ton per year, corresponding to 1400 ton per year for each MWe HP unit.

The calculated reduction in CO2 emissions is likely not obtained in praxis as the supply of electricity and district heating is subject to carbon quotas. However, the reduction carries an economic benefit in terms of freed carbon credits. Considering investment costs of €2,0 mill. per MWe[8] for the HP unit plus €0,4 mill. for ground source heat uptake[9], an economic discount rate of 6 %, and an assumed life time of 20 years at given O&M costs, the economic costs of freed carbon credits amount to €214 per ton according to EnergyPLAN and €242 per ton according to SIVAEL. This is significantly higher than projected carbon credits at €23 per ton readily supports.

The result supports the understanding that the introduction of unconstrained large-scale heat pumps in district heating results in a more resource-efficient energy system, better

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[8] Excluding CS and chimney core in stainless steel, i.e. 76% of the estimated investment costs for the CHP-HP-CS concept [22]
[9] Estimated at €0,16 mill. per MWq excluding costs of land [22].

domestic integration of intermittent supply (reduced exports), and non-cost-effective CO2 emission reductions.

However, EnergyPLAN and SIVAEL does not readily allow for the evaluation of more advanced concepts for relocation, including the CHP-HP-CS concept. Furthermore, neither model considers the potential benefits that relocation technologies may provide in terms of possibly avoided infrastructure costs. Also, neither model allows for any detailed understanding of the consequences of how the integration of an HP unit affects the operational strategy of a cogenerator.

9. COMPOSE: A hybrid project-system approach

The article "Technical and economic effectiveness of large-scale compression heat pumps and electric boilers in energy systems with high penetration levels of wind power and CHP" submitted for publication to Energy in April 2007 [10], presents the modelling framework COMPOSE for assessing relocation options that combines operational design model energyPRO [18], historical production data from Energinet.dk, and various projections from the Danish Energy Agency's energy system model RAMSES [23], optionally system data from EnergyPLAN.

COMPOSE, which is an acronym for *Compare Options for Sustainable Energy*, allows for the evaluation of user-defined energy projects in user-defined systems. The mission is for COMPOSE to combine the strength of energy project operational simulation models with the strength of energy system scenario models in order to arrive at a modelling framework that supports an increasingly realistic and qualified comparative assessment of sustainable energy options.

COMPOSE currently allows for the evaluation of a project's relocation coefficient, economic cost-effectiveness of relocation, economic costs, as well as both local, avoided, and system-wide CO2 emissions and consumption of primary energy resources.

Figure 3 illustrates the overall model flow chart for COMPOSE. In essence, COMPOSE imports an optimized operational strategy from energyPRO, and combines the resulting hourly energy balance for a given year with projected annual and hourly characteristics of the system in which the project is located.

Figure 4 illustrates the internal structure of COMPOSE. At the core of the model, the user defines a system and a project. The system consists of five parent components: energy system, economic system, environment system, risk specifications and methodology options. The project consists of two major child components: process and demand.

One key methodological feature is the way most variables are associated with both an annual projection that describes how the mean annual value will develop over the planning period, as well as an hourly profile that describes how the mean annual value is distributed into hourly values for each year in the planning period. COMPOSE imports annual and hourly profiles from Energinet.dk and RAMSES, and optionally also from EnergyPLAN, while projects, including the optimized hourly production profile for each production unit, are imported from energyPRO. It is furthermore possible to localize hourly profiles using monthly climate data from RetSCREEN [24], for example cloning a recorded Danish hourly production profile for solar cell production into a simulated hourly production profile for Trieste in Italy.

Another key methodological feature is the way the interface between the energy project and the energy system is modelled. COMPOSE applies a least-cost dispatch model for central electricity generation that relies on how user-selected candidate marginal electricity producers are expected to *bid and stay* in the electricity market (the spot market) according to each producer's long-term marginal production costs. Rather than relying on short-term marginal costs for identifying operational changes in central electricity generation, COMPOSE suggests a simplified methodology by which the dispatch analysis reflects the long-term consequences of changes.

To support an integrated and consistent evaluation, COMPOSE handles each of the candidate marginal plants in the dispatch model as any other COMPOSE energy project, thereby subject to similar assumptions and algorithms.

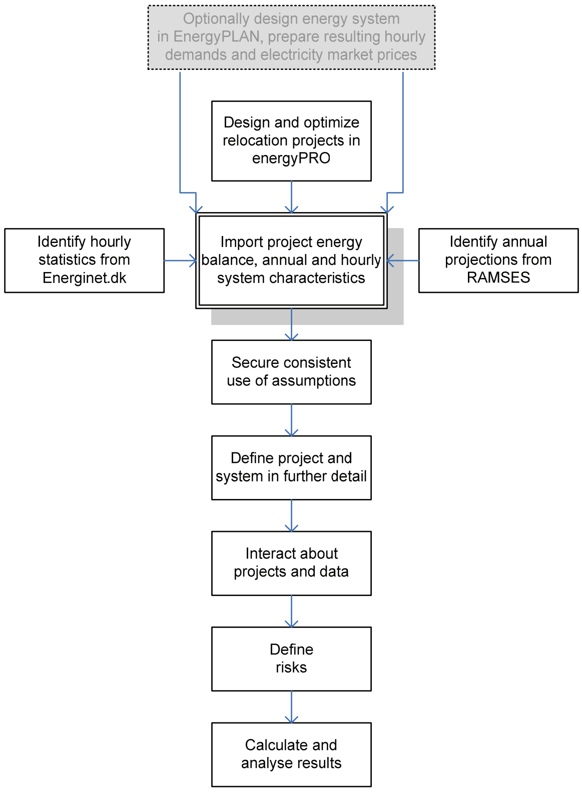

Figure 3: COMPOSE: Model flowchart.

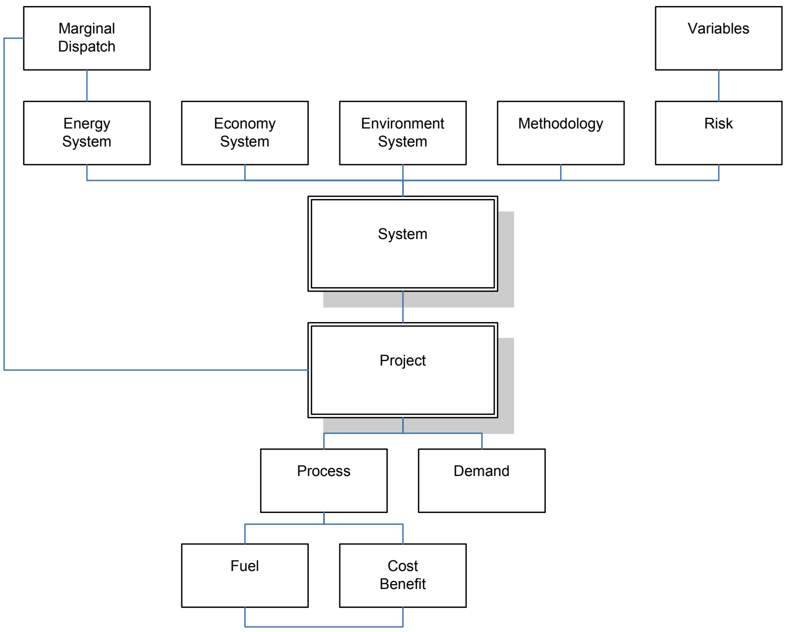

Figure 4: COMPOSE: Structure for defining energy project and system.

Figure 5 illustrates the structure of the energy system component by which the marginal dispatch model refers to any number of user-defined projects. Also the energy system holds an hourly projection for electricity demand and intermittent supply, which is of particular importance in arriving at a project's relocation coefficient.

The analyses in [10] are subject to economic fuel costs and electricity markets projected by the Danish Energy Agency / RAMSES as of February 2007 [25]. While avoided costs in central electricity generation are given by the projected annual and hourly prices in the electricity market - projected annual means according to RAMSES and hourly fluctuations assumed similar to historic markets according to Energinet.dk market data, in [10] the 2006 spot market, optionally according to EnergyPLAN - COMPOSE's least-cost dispatch model is applied for identifying marginal producers in central electricity production with respect to avoided primary energy consumption and emissions. Figure 6 illustrates the consequences of this dispatch model for the analyses in [10], where three candidate marginal producers towards 2025 were defined for the West Danish energy system: coal-fired power plants at 48 % fuel-to-electricity efficiency, natural gas fired power plants at 55 % fuel-to-electricity efficiency, and off-shore wind power. The dispatch model settled that for electricity market prices below €33,3 per MWh, found to be the long-term marginal production costs of coal-fired power production on given assumptions, wind power is the marginal producer. Between €33,3 and €44,7 per MWh, coal-fired power plants is the marginal producer, while natural gas fired power plants is the marginal producer spot market prices above €44,7 per MWh, corresponding to the long-term marginal production costs of natural-fired power production. Detailed techno-economic assumptions with respect to projected fossil fuel prices, O&M costs, and the electricity spot market are presented in [10] as well as in the database included with COMPOSE.

Finally, COMPOSE allows for the user to specify uncertainty ranges for a number of selected variables including heat demand, electricity demand, intermittent supply, and economic discount rate. These uncertainties are then applied in extensive Monte Carlo risk assessments, subsequently allowing for the computation of statistical means and frequencies for individual results.

COMPOSE is included on the CD-ROM that accompanies this thesis, and may also be downloaded from http://energyinteractive.net. COMPOSE is a client-server application with a remote database server and includes features to support interactivity, therefore Internet access is required while using the model.

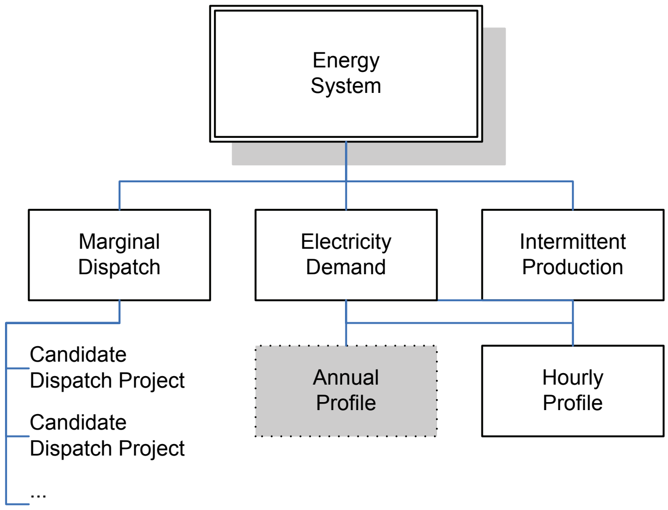

Figure 5: COMPOSE: The energy system component.

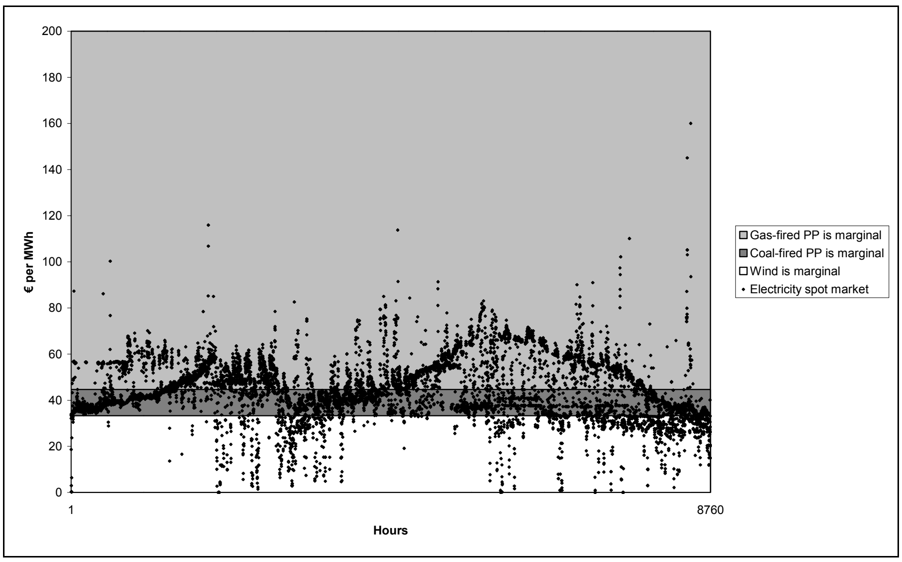

Figure 6: Marginal dispatch in central electricity generation as a function of 2006 spot market price fluctuations.

10. Consequences of advanced relocation concepts

In [10], the COMPOSE modelling framework is applied in the detailed operational optimization of an existing 3,5 MWe natural-gas fired cogeneration plant located in the West Danish energy system. The plant is suggested to be typical to about 25 % of the technical potential for large-scale heat pumps with respect to the electricity generating capacity of distributed cogenerators. Consequences are assessed for operating the plant over a period of 20 years subject to economic fuel costs and electricity markets projected by the Danish Energy Agency as of February 2007 [25].

Figure 7 illustrates a sample of the operational consequences of adding an HP unit to an existing CHP plant. The figure shows the dispatch of production units for one week in October optimized according to least economic costs including carbon credit costs, under given technical constraints. The top figure is current operation, while the bottom figure is one of the CHP-HP-CS concepts (Option B).

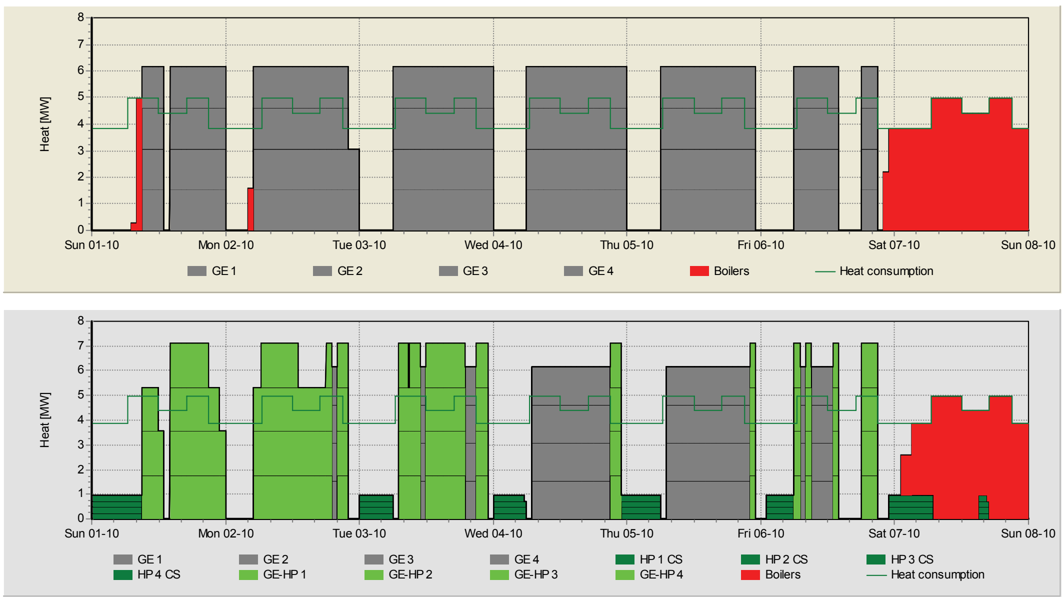

Figure 7: Sample heat production by production unit for first week of October 2006 (Week 40). Top figure is for current operation (Reference). Bottom figure is for CHP-HP-CS with concurrent operation of CHP and HP units allowed (Option B). energyPRO charts from [10].

Most clearly it appears that the integration of an HP/EB unit reduces boiler operation, but also the plant's load factor is obviously reduced. Figure 8 illustrates the resulting load curves for most of the options under analysis. The article finds that for Option A, that simply adds an HP unit to the plant's for concurrent operation of CHP unit and HP unit, the plant's full-load hours are reduced from currently 5,877 down to 5,185, while adding a Cold Storage (Option B) further reduces the number of full-load hours to 5,073. Disallowing concurrent operation of CHP unit and HP unit (Option C) recovers the number of full-load hours to 5,525. Noticeably adding a ground-source HP unit with similar heat production capacity as the CHP unit (Option E) reduces the number of full-load hours to 4,740.

It appears that the consumption of electricity in low-load periods affects the ability of the CHP unit to produce in intermediate-load and high-load periods. As it turns out, this has a surprising impact on the system-wide environmental consequences of integrating HP/EB units with an existing CHP unit.

For options that are constrained by heat recovered from flue gasses as low-temperature heat source (Option A, B, and C), the benefits of constrained utilization of zero-emission electricity in low-price periods, where wind power is the marginal producer, is compromised by the reduced benefits of the CHP unit to supply electricity during periods in which coal-fired power is the marginal producer. In result, the system-wide carbon dioxide emissions increase between 13 % and 22 % for these options. The lowest increase is for Option C, which disallows concurrent operation of CHP unit and HP unit. In conclusion, the article finds that any constraints on the low-temperature heat source are a disadvantage to the potential for an integrated HP unit to provide system-wide energy and environmental benefits. This disadvantage may be eased by disallowing concurrent operation of CHP unit and HP/EB unit.

However, the article finds that the integration of an HP/EB unit results in increasing the plant's relocation coefficient (*Rc*) currently at 0,518, up to a maximum of 0,593 (Option E). Looking at Option B, that adds a 250 m3 cold storage to Option A, the article finds that *Rc* increases from 0,540 to 0,547, and that the HP unit's share of total heat production increases from 8,5 % to 10,1 %.

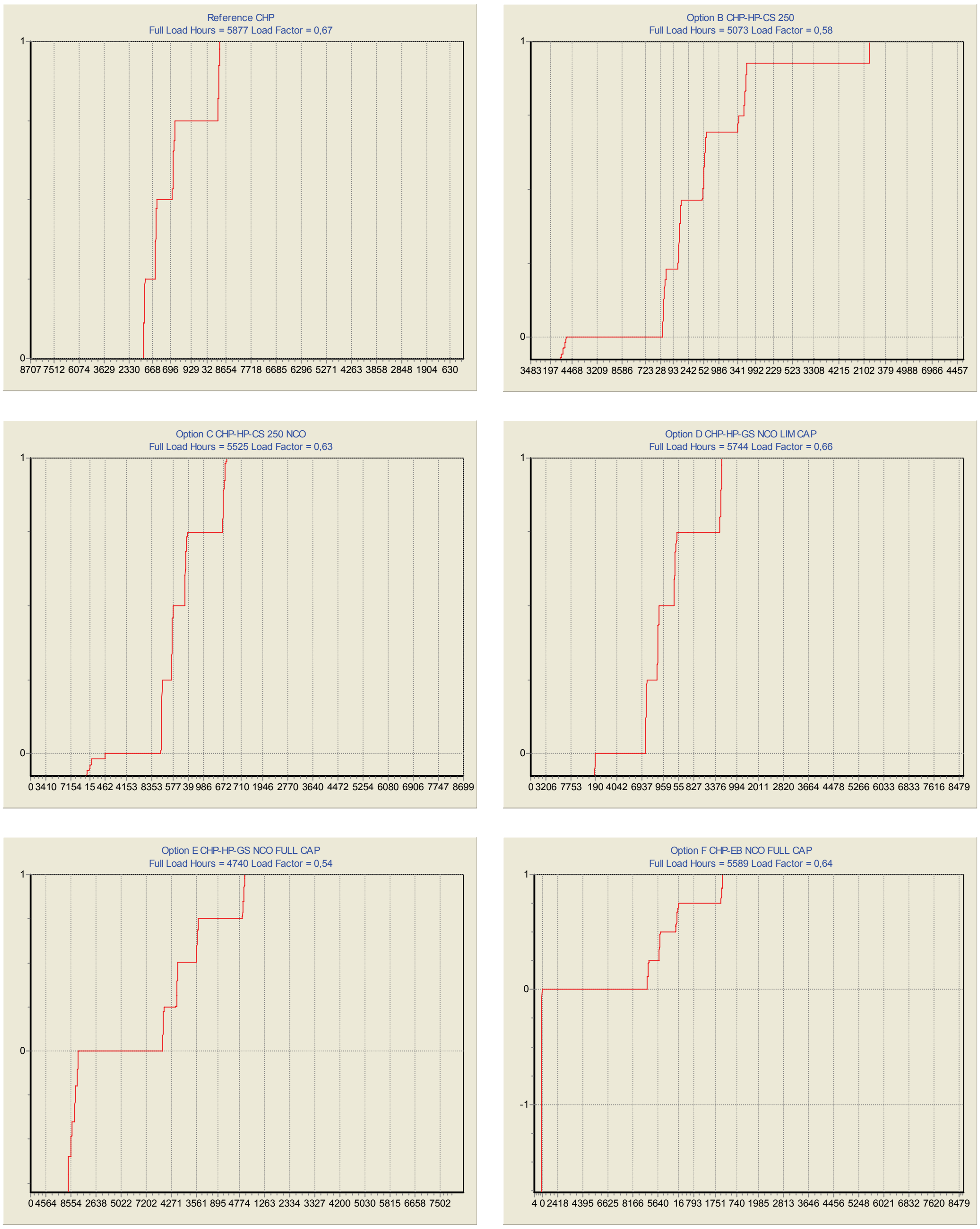

Figure 8: Load curves for 6 of the options analysed in [10]. Only Option A is excluded. Charts from COMPOSE.

In conclusion, the integration of HP/EB units support the domestic integration of wind power even without the ability to operate the HP unit independently from the CHP unit, but the addition of a cold storage for independent HP unit operation further improves the relocation coefficient by allowing for the plant better to utilize the HP unit in low-price periods.

With respect to the economic cost-effectiveness of options, the article finds that the integration of an HP/EB unit allows for reducing the overall levelized short-term marginal heat production costs from 2 % (Option C) up to 16 % (Option E). However, taking investment costs and fixed O&M costs into account, carefully settled in collaboration with leading manufacturers, the article finds that the median levelized economic costs of heat production – which is the mean of discounted costs over the planning period for all of the 200 trials that were calculated for each option subject to a number of specified uncertainties – increases with 2 % for Option D, with 5 – 8 % for Options A, B, C, and F, and with 59 % for Option E. In conclusion, the integration of all of the relocation conception under analysis, optimized for cost-effective operation under given techno-economic constraints, results in increasing economic costs of heat production. Option E that displays the highest *Rc* and the lowest CO2 emissions is also the most expensive heat producer even without valuating the costs of land for the extensive ground-source heat recovery system involved. The high levelized production costs are explained by an investment cost of €4,7 mill. for doubling the plant's heat production capacity, also resulting in the highest fixed O&M costs.

However, it seems reasonable to accept that relocation may come at an increased economic cost, as it may be argued that domestic integration of intermittent supply is avoiding investments in cross-national and even intra-national transmission infrastructure. The article does not attempt to monetarize this benefit, but rather considers the cost-effectiveness of relocation. The article finds that Options B and D provide the most cost-effective relocation, offering an economic shadow cost for relocation around €11,000 per increased *Rc*-% (Figure 9).

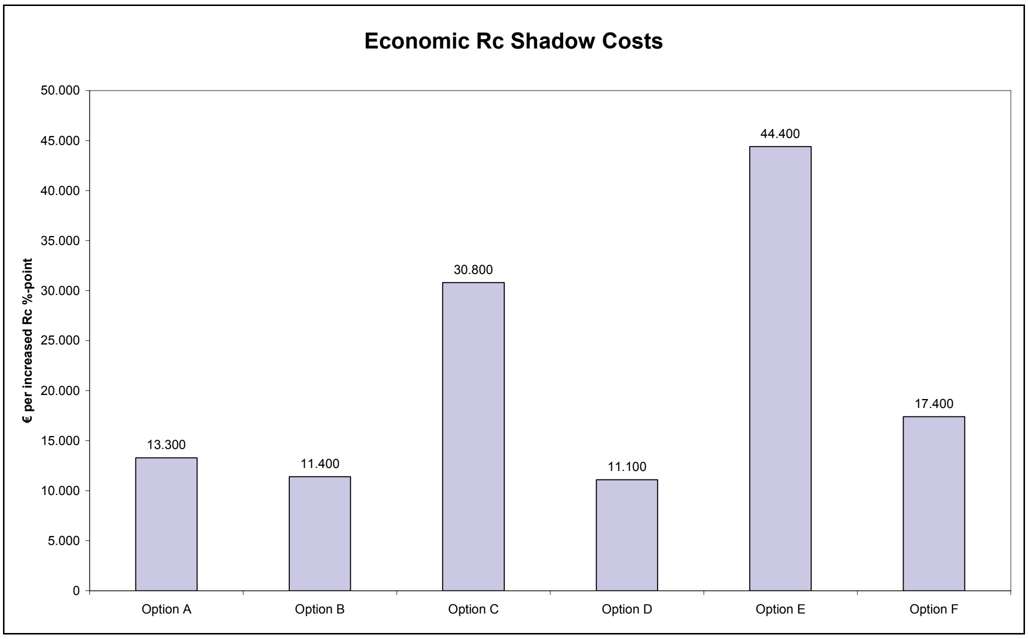

Figure 9: Economic Rc shadow costs for relocation options under analysis.

In conclusion, the article supports a better understanding of how the HP/EB unit interacts with a CHP unit, including the drawback of constraints on the low-temperature heat source, the overall benefits of adding a cold storage, and the environmental benefits associated with disallowing concurrent operation of CHP unit and HP unit.

In reflection, the article also provides a better understanding of how much to expect from large-scale heat pumps in providing any significant amount of relocation. If HP units are going to co-exist with CHP units in a cost-effective manner, the thesis finds that the electric capacity of an HP unit should better be less than 10 % of the CHP unit's installed electricity generating capacity. As such, a combination of CHP-HP-CS concepts (Option B and C) and the CHP-HP-GS concepts with limited HP capacity (Option D), would roughly allow for the cost-effective integration of no more than 150 MWe large-scale heat pumps with existing distributed cogenerators in the Danish energy system. While this would affect the plants' operational strategies, increasing their wind-friendliness, and allowing for them to provide certain balancing services, it does not even nearly replace the need for central power plants in providing balancing services, nor solve the problem associated with ambitious targets for large-scale penetration of intermittent resources.

An idealized use of the relocation coefficient and the relocation cost-effectiveness metrics introduced with this thesis would be to create a “supply-curve” assessment of relocation options for increasing the relocation coefficient of distributed generation. Figure 10 illustrates a proxy sample of applying such idealized methodology, making the cost of establishing cross-national electricity exchange infrastructure the cost-effectiveness “cut off” for measures that would support domestic integration of intermittent supply.

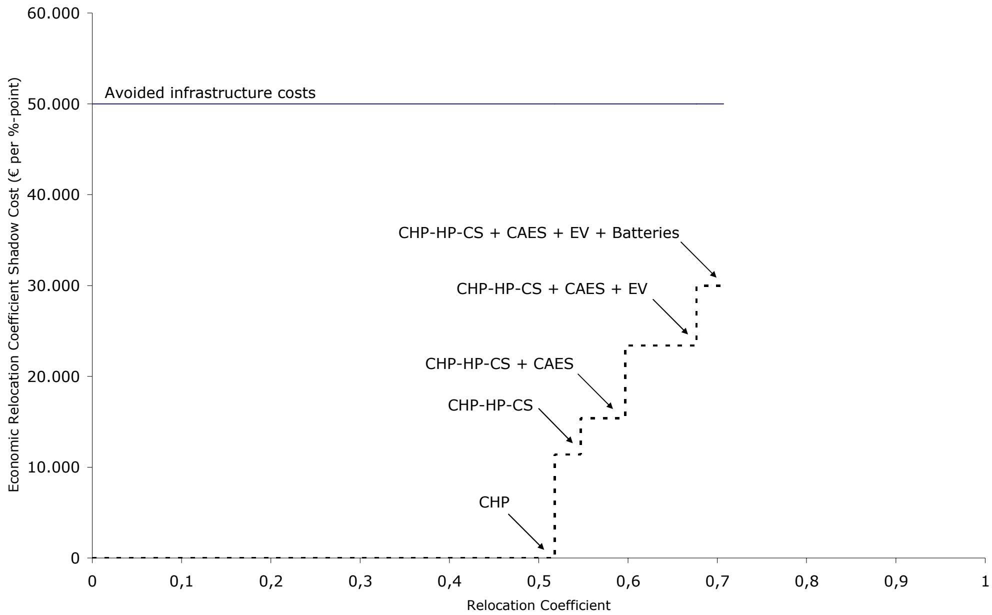

Figure 10: Proxy ranking by economic relocation cost-effectiveness and relocation coefficient for illustration of methodology only. All are random sample numbers except for CHP and CHP-HP-CS.

The methodological framework developed for these analyses does not internalize the economic value of providing balancing services. The balancing markets are considered to be a non-quantified side benefit, which may be said to be expressed by increasing relocation coefficients, but the benefits are not monetarized. Furthermore, the methodology does not consider any feed-back effects on electricity markets that large-scale penetration of relocation options would result in. Finally, it is important to note, that plant operation for all options in [10] is optimized and simulated under narrow economic costs and benefits excluding fiscal taxes, however including carbon credit markets. The methodology does not provide an evaluation of the economic consequences of plant operation optimized according to financial costs, for example by use of economic shadow costs as in the energy system analyses in [15]. This particular methodological choice serves the purpose of the article, which was to assess to which degree society should take interest in these options, simulating the operation of relocation concepts according to socio-economic least-cost principles, on the basis of which the energy, environmental, and socio-economic consequences are subsequently evaluated.

However, in a previous article "Large-Scale Heat Pumps In Sustainable Energy Systems: System And Project Perspectives" published in *Journal of Thermal Science* in 2007, options B and D are evaluated under constraints of financial costs of operation. While the article suggest that financial production would increase by up to 10% with any of these options, the key point of the article is that if the financial costs of using electricity for district heating production should be reduced, either due to fiscal measures or due to markets, any installation of HP units with heat production capacities similar to that of the CHP units could easily jeopardize efforts to maintain the principle of cogeneration in the Danish energy system. HP units with full heat production capacity are not an alternative to electric boilers; rather would low marginal financial production costs for HP units make them an alternative to cogeneration. Policy instruments should therefore be carefully designed to promote the integration of heat pumps with lower heating capacities than that of the CHP unit not to put the principle of distributed cogeneration of heat and power in the energy system at risk.

11. Policy instruments towards domestic integration

In December 2005, the Danish parliament passed legislative changes intended to stimulate the use of electricity in very low-price periods for district heating production. Law 1417/2005 was ratified by the European Commission in November 2007. The Commission was initially weary about whether the legislation would favour particular producers, but was ultimately convinced that the legislation would benefit only consumers in district heating. L1417 is likely the first attempt by any country to introduce fiscal instruments intended to influence the operation of cogenerators better to support large-scale penetration of wind power.

The use of electricity for heating production, also self produced electricity, is by default subject to a fiscal tax of €0,089 per kWh electricity including CO2 tax. L1417 harmonizes energy and environmental taxation rates for fuels used in district heating production to €6,7 per GJ delivered heat. The reduced fiscal tax rate for electricity is available only to cogenerators, and only for inconcurrent operation of CHP unit and HP/EB unit. L1417 reduces the fiscal tax rate for consuming one kWh of electricity for heat production in an EB unit by 70 %. But as the fiscal tax rate is calculated on the basis of heat production, not on the basis of electricity consumption, L1417 penalizes HP units, for which a COP of 3,7 fiscal taxation would actually increase. With L1417, the higher the conversion efficiency, the higher the fiscal taxation. L1417 and its consequences is analyzed and discussed in various communications [26,11,13], and it is argued that the instrument does not do a sufficiently good job in preparing for domestic integration of intermittent resources.

In Danish-language feature articles "A minor adjustment of taxation rates could mean a breakthrough for large-scale heat pumps, more efficient cogeneration, and the integration of wind power" [27] and "Let's future-proof distributed cogeneration" [28], both published in *Ingeniøren*, I have presented an idea that would make cogenerators eligible for reimbursement of fiscal tax for electricity used in heat pumps limited to a maximum of 10 % of the cogenerators electricity production. I have argued that this instrument should be considered neutral to the fiscal budget as industry is already considering solutions for integrating large-scale heat pumps with cogenerators using hydraulics simply to avoid electricity taxation. This instrument would allow for producers to choose an electric compressor rather than a mechanical compressor, thereby also opening up to concepts that would support domestic integration of intermittent resources, like the CHP-HP-CS concept. The 10 % limit is suggested by the findings of this thesis related to cost-effective sizing of HP units that would also not jeopardize the principle of cogeneration.

This idea for a tailored and careful fiscal instrument to support large-scale heat pumps, more efficient cogeneration, and the domestic integration of wind power that would not jeopardize principles for cogeneration, is adopted as one of the policy recommendations in ”Energy Plan 2030” published by the Danish Association of Engineers [21] in 2006.

12. Findings in perspective of recent studies

The findings in [10] particularly challenges the findings of studies that suggests for the introduction of large-scale heat pumps in district heating to be a "no-regret" option, representing certain economic and environmental benefits.

The concept of integrating efficient large ground-source heat pumps in district heating production for the purpose of supporting large-scale penetration of wind power and cogeneration was analyzed as part of the research project at Aalborg University "Local Energy Markets" published in January 2004 [29]. Here it was assumed that the required levelized investment costs including fixed O&M costs for integrating large-scale heat pumps in distributed generation would correspond roughly to an investment of €0,5 mill. per MWe, and it was found that investments in heat pumps was cost-effective even at current levels of wind power penetration. The thesis finds that investment costs for relevant concepts are likely to be at least 5 times higher than assumed in this study.

In ”Energy Plan 2030”, prepared by the Danish Association of Engineers [21], investment costs and fixed O&M costs reflect the findings also applied for some of the options in this thesis upon consultation [22], corresponding to investment costs of €2,7 mill. per MWe. Applying EnergyPLAN, the study finds that the integration of 450 MWe large-scale heat pumps would reduce the economic costs of energy production in 2030 by €263 mill. before depreciation of investment costs and fixed O&M costs, amounting roughly to a levelized cost of €82 mill. per year at a discount rate of 3 % per year, suggesting for the net benefits to amount to €181 mill. per year. However, these benefits are not arrived at by the partial inclusion of heat pumps in the reference scenario, but by removing heat pumps from the alternative scenario, i.e. they represent the benefit of heat pumps in a visionary scenario in multiple ways different from the reference scenario, particular with respect to wind penetration levels, which is at 60 % of total supply. Noticeably, in the visionary scenario, heat pumps are replacing almost 75 % of boiler operation and 20 % of cogeneration, and are basically operated as base load heat producers with 7100 full-load hours. In this thesis, [10] simulates the introduction of heat pumps quite differently finding that for concepts like CHP-HP-CS or CHP-HP-GS only the installation of an unconstrained HP-GS unit with a heat production capacity similar to that of the CHP unit is able to replace 100 % of boiler operation and 19 % of CHP unit operation, while for more cost-effective options, boiler operation is reduced by 25 % - 40 %, while CHP unit operation is reduced by 2 % - 14 %. Simply extrapolating the results in [10] with respect to costs, it is found that introducing 450 MWe heat pumps as CHP-HP-CS or CHP-HP-GS would result in net annualized economic costs of between €30 mill. and €55 mill.

In ”The Future Danish Energy System”, prepared by The Danish Technology Council [30], the so-called “combi-scenario 2025” includes the consequences of allowing 264 MWe large-scale heat pumps to supply almost 17 % of the total district heating production in 2025. At €3,5 mill. per MWe, investment costs, and also fixed O&M costs, are higher than for the integrated options suggested by the thesis. The heat pump option is not subject to any partial evaluation, but the combi-scenario is found to increase the economic costs of energy system operation by €214 mill. per year compared to the assumed 2025 reference scenario. While the study evaluates the heat pumps as integrated in heat-only production, it may be argued that simply assuming 4500 full-load hours for all heat pumps without considering reducing the number of full-load hours for distributed generators, fails to consider the constraints given by actual plant operation as explored with this thesis. The thesis hypothesizes that the introduction of large-scale heat pumps primarily will take place in distributed generation which would allow for advanced relocation concepts, but would then also reduce the load factor of cogenerators.

However, the methodology of these studies differs from the approach applied in [10]. Both studies analyses the inclusion of heat pumps for a single year in an energy system very different from the current system. In [21], the wind power penetration level in 2030 for which the analyses are prepared is assumed to have reached 60 %. In [30], wind power penetration levels in 2025 are assumed to be at 50 %. In [10], the Danish Energy Agency's annual reference development scenario as modelled by RAMSES is applied in modelling relocation concepts over a period of 20 years from 2006-2025 during which the wind power penetration level will increase to 29 %.

With respect to electricity spot market prices and fossil fuel prices, the thesis applies Danish Energy Agency projections for 2006-2025 as of February 2007 [25], which includes projected prices for 2030; USD55 per barrel for oil, and USD60 per ton for coal. In [21], an oil price of USD68 and a coal price of USD63 is assumed for 2030, while [30] assumes an oil price of USD50 and a coal price of USD55 for 2025.

But most importantly, both studies are assuming for heat pumps to substitute boiler operation rather than cogeneration, allowing for high load factors of the heat pumps. In this respect, both studies are not limited to considering the integration of heat pumps with cogenerators for which boiler operation is often limited to peak and reserve loads, often supplying a relatively small share of total heat production. Nor does the studies consider for the operation of heat pumps to be constrained by the availability of low-temperature heat sources.

In conclusion, the combined findings of these studies and the findings offered by the thesis, it is suggested that the technical and operational concepts, by which heat pumps are integrated into the energy system, is critical to the cost-effectiveness of this option. The two studies are suggesting that concepts allowing for the heat pump to substitute boiler operation, making the heat pump enter as a base-load heat producer, are likely to be cost-effective. The thesis is suggesting that concepts for integrating heat pumps with cogenerators comes with significant variations in resulting substituted boiler operation and cogeneration, which may in some cases (Option C) even increase boiler operation, reducing only cogeneration. For the concepts in [10], the heat pump enters as an intermediate-load heat production unit with full-load hours between 1350 and 4250 according to concept, all resulting in annualized costs of heat production that are 2 % to 8 % higher for Options A-D, and 59 % higher for Option E.

Finally, in another recent study, Energinet.dk's 2007 system plan [7] considers the integration of 125 MWe large-scale heat pumps into strategic district heating areas by 2025 in an energy system where 44% of total wind production would come from wind power. In this study, heat pumps are found to reduce critical excess by 60 GWh out of a total critical excess of 700 GWh. The thesis finds that 125 MWe CHP-HP-CS or CHP-HP-GS concepts would likely consume around 160 GWh per year, while reducing cogenerator electricity output by about 600 GWh per year. However, the thesis has not attempted to quantify the problem in terms of excess electricity production.

13. Interacting values, beliefs, and rationalities

As "[...] planners and other agents of intervention continue to make assumptions about the values, beliefs, or rationalities of those for (or with) whom they plan, which frequently do not hold", as concluded by planning researcher Vanessa Watson from her assessment of planning processes in South Africa [31], the thesis has applied an *interactive energy planning framework* that combines methodologies in PBL, integrated energy planning, and phronetic planning research [32], while particularly emphasizing the need for developing accurate techno-economic software that better supports for researchers and operators in distributed generation to interact about problems and solutions.

COMPOSE, EnergyInteractive.NET[10], and FJERNVARMEPUMPER.DK[11], are major outputs of the methodological focus that the thesis has had on interactivity.

COMPOSE and EnergyInteractive.NET constitutes the kind of frameworking tool envisioned in the book chapter "Interactivity in Planning: Frameworking Tools" published in the reader "Tools for Sustainable Development" [33] in 2007. The article

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[10] http://energyinteractive.net
[11] http://fjernvarmepumper.dk

formulates 10 requirements for a software tool to be supporting interactivity in planning, including that it should be accurate in addressing technical and economic problems experienced by stakeholders, that it should complement proprietary tools, and that it should be stimulating users to exchange information about projects and data.

Interactivity is also the subject of the conference article “Interactive energy planning: Towards a sound and effective planning praxis” [34] presented at the World Renewable Energy Congress in Florence in August 2006. The article highlights the importance of improving the way interactions are monitored and evaluated in planning. The article discusses findings from research into integrated energy planning practices and phronetic planning research in the context of recent innovations in European energy planning, mainly Denmark’s success with wind power [35], and UK’s success with curbing urban traffic in London [36]. The opening hypothesis is that neither neo-classical economic theory, nor any instrumental rationality may have prepared the success of these experiments. It is suggested that, in praxis, change does not arrive from trivial rational calculations, but rather from judgment generated by creation and coordination of expectations through social interaction [37]. The article finds that interactivity is central in Michel Foucault’s works, suggesting that global structures of power and interests are best analyzed by looking at local tactics of domination, concretely by the way people interact along the borderline of their reign [38].

The thesis has established COMPOSE and EnergyInteractive.NET as a starting point for researching better ways of applying techno-economic planning software that support and monitor interactivity. The thesis expects for COMPOSE and EnergyInteractive.NET increasingly to contribute in discussions about sustainable energy experiments.

FJERNVARMEPUMPER.DK is an output from a series of workshops targeting operators in district heating on the operational, technical, and economic perspectives of large-scale heat pumps. The workshops have been organized and implemented under the auspices of the Danish District Heating Association since November 2006. So far three workshops have been held for a total of 45 operators in district heating. The next workshop will be held in September 2008.

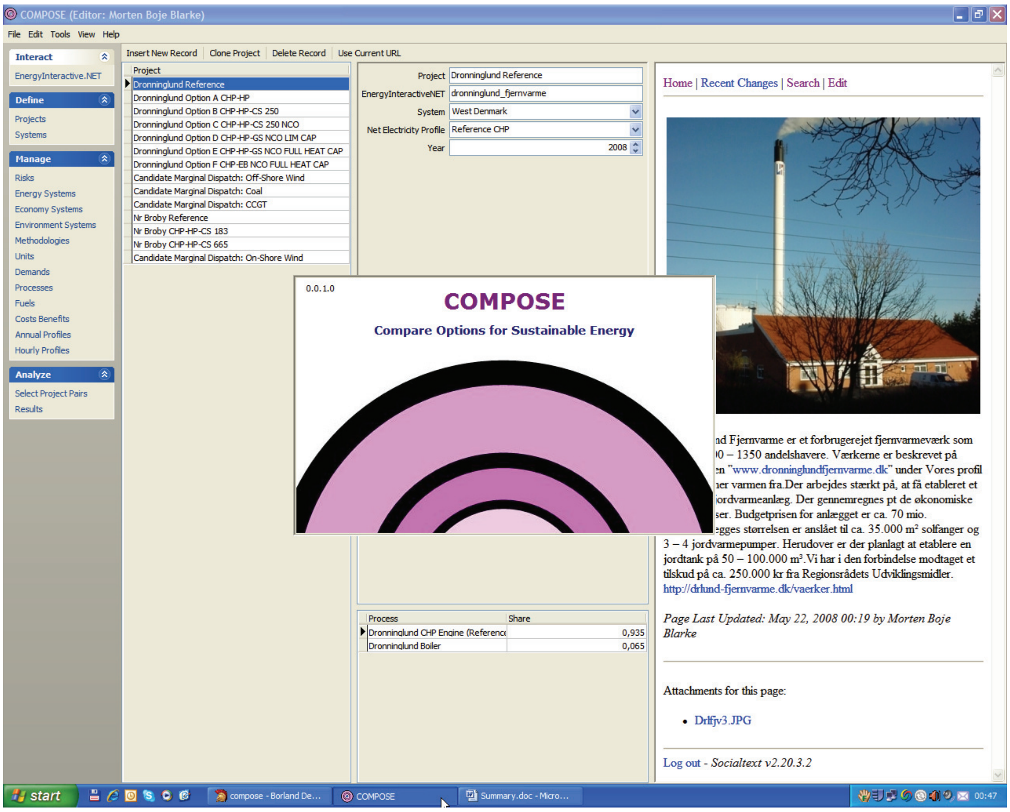

Figure 11: COMPOSE: Screenshot.

14. Postscript

Exactly 500 years ago, Leonardo da Vinci was adding yet another couple of inspired words and sketches to his collection of papers. Throughout his life, da Vinci intended one day to publish his scientific ideas in a proper book, but he never managed to do so. It is only by virtue of one of his friends, who, upon da Vinci's death, managed to collect and safe keep da Vinci's unorganised pile of papers that we know about the groundbreaking discovery that da Vinci made on March 22 in 1508. Observations and reflections, of which we know little, had led da Vinci to sum up, on a sheet of paper, in unusually large letters: "THE SUN DOES NOT MOVE". As we know, he actually got away with it.

108 years later, Galilei Galileo did not, boldly maintaining, in a letter to the Grand Duchess Christina that "... the Sun is located at the centre of the revolutions of the heavenly orbs and does not change place". The Inquisition had had enough –

and Galileo was accused of heresy. But that's not really the point here.

Rather, we may realize by the mere size of the letters in da Vinci's written observation that he must have felt astonishingly invigorated and at the top of his game on that Wednesday[12] in March. And perhaps it was an urge to capture the nature of his conviction further that made him go on to include, on the same paper sheet, as the final sentence, what was to become perhaps his most famous aphorism: "Wisdom is the daughter of experience".[13]

Today, wise decisions are truly needed in mission critical areas of space ship earth, but is experience global? Is wisdom? Does the experience and sound judgment of one lead to a decision that is sound for everybody? "Experience does not ever err; it is only your judgment that errs in promising itself results which are not caused by your experiments", da Vinci later hinted. Is judgment really experimental by nature, and wisdom but an experimental attempt to make sense? Perhaps so, but more so, experience is a fertile land that carries offsprings according to the seed that men sow.

The experiment is the seed, the nucleus of wisdom, and life. And this thesis has basically dealt with a very real experiment of potential global socio-economic implications: the Danish attempt to establish a safe, cost-effective, and reliable energy system that relies on intermittent renewables in combination with distributed generation. The Danish experiment is unique and important to the global pool of experiments that tries to tackle the energy system's contribution to global warming.

So far, the Danish experiment has proven that a wind power penetration rate of up to 25 % of annual electricity supply is possible without any significant technological changes in distributed generation. But higher penetration targets for wind power, perhaps up to 50 % by 2030, calls for technological changes that will fundamentally change the role of distributed generation. It seems that Denmark is in a unique position for an experiment that attempts to handle such high penetration

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[12] According to the Julian Calendar (http://www.guernsey.net/~sgibbs/roman.html)

[13] Sometimes translated as "Wisdom is the daughter of the experiment",

rates by domestic integration. And that the feasibility of this experiment could be threatened by plans to invest €-billions in infrastructure to increase electricity exchange with neighbouring energy systems.

It would be wise to take the first steps towards the vision for which Assoc. Prof. Klaus Illum, Aalborg University, in 1987 received the Statoil Reward. Illum's saw it possible for so-called LOCUS[14] energy systems that involves the integration of large-scale heat pumps with distributed cogenerators to serve very high penetration rates, while reducing the need for fossil fuels and central power plants [39,40].

20 years later, in February 2007, a group of partners including Aalborg University has been awarded €1,3 mill. for a full-scale CHP-HP-CS demonstration project [41]. With transcritical CO2 large-scale heat pump technology ready to serve, Illum's vision for a distributed energy system with large-scale heat pumps is as relevant as ever. But the challenge of handling large-scale penetration of cogeneration and intermittent resources is not solved by this experiment alone.

Also the original LOCUS systems did not just include heat pumps, but also the integration of solar heating, hydrogen storage, electric vehicles, and other storage and relocation options. The thesis provides evidence to the fact that large-scale heat pumps will not singlehandedly solve the problem of integrating intermittent resources. Not at all, so to say.

But while options for domestic integration are coming along, the biggest threat to the continuation of the Danish experiment, and the exploration and development of options towards a *domestic integration strategy* for intermittent supply is an *open access strategy* that would expose the Danish energy system to powerful and conflicting interests at play in defining global strategies for sustainable energy. In [1], the thesis suggests the existence of three basic technology strategies by which a sustainable energy system may be accomplished: *nuclear/hydro*, *coal with sequestration*, and *intermittent renewables in combination with distributed generation.* While the severity of the climate crisis requires for global sustainable energy policies to consider all of these basic sustainable

[14] LOcal Cogeneration Utility Systems.

energy strategies on their own terms, a tallying of both current technology strongholds and public research priorities in US, Japan, and EU, reveals the dominating attention that nuclear and fossil strategies for sustainable energy receives (Figure 12). As for EU alone, the most recent mapping of energy R&D in EU member states, concludes that 40 % is dedicated to nuclear energy, 20 % to renewables, and some 10 % to fossil fuels and energy efficiency [42].

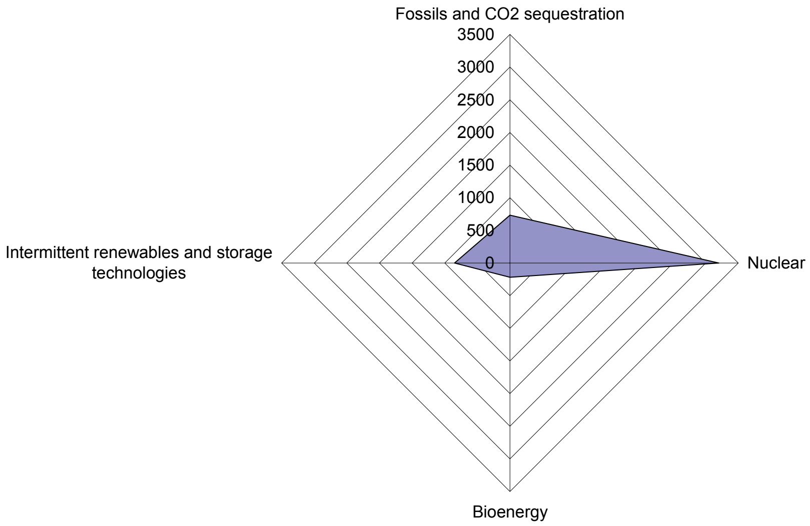

Figure 12: Total public R&D spending in Japan, USA, and EU-13 grouped by sustainable energy system solutions (mill. EUR). Based on own categorization of data from the European Commission [42].

What's really important is for the Danish and the global society to understand the need to cherish the Danish experiment for domestic integration. This experiment involves further research into options for domestic integration, including commencing the integration of large-scale heat pumps in distributed generation. Denmark is currently the obvious candidate for being the first to answering the central question in years to come: Is a domestic integration strategy for sustainable energy doable and feasible?

Denmark should be careful not to throw away the key to this answer.

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Primary publications

LARGE-SCALE HEAT PUMPS IN SUSTAINABLE ENERGY SYSTEMS: SYSTEM AND PROJECT PERSPECTIVES

by

Morten B. BLARKE and Henrik LUND

Original scientific paper
UDC: 621.57
BIBLID: 0354-9836, *11* (2007), 3, 143-152

This paper shows that in support of its ability to improve the overall economic cost-effectiveness and flexibility of the Danish energy system, the financially feasible integration of large-scale heat pumps (HP) with existing combined heat and power (CHP) plants, is critically sensitive to the operational mode of the HP vis-à-vis the operational coefficient of performance, mainly given by the temperature level of the heat source. When using ground source for low-temperature heat source, heat production costs increases by about 10%, while partial use of condensed flue gasses for low-temperature heat source results in an 8% cost reduction. Furthermore, the analysis shows that when a large-scale HP is integrated with an existing CHP plant, the projected spot market situation in The Nordic Power Exchange (Nord Pool) towards 2025, which reflects a growing share of wind power and heat-supply constrained power generation electricity, further reduces the operational hours of the CHP unit over time, while increasing the operational hours of the HP unit. In result, an HP unit at half the heat production capacity as the CHP unit in combination with a heat-only boiler represents as a possibly financially feasible alternative to CHP operation, rather than a supplement to CHP unit operation. While such revised operational strategy would have impacts on policies to promote co-generation, these results indicate that the integration of large-scale HP may jeopardize efforts to promote co-generation. Policy instruments should be designed to promote the integration of HP with lower than half of the heating capacity of the CHP unit. Also it is found, that CHP-HP plant designs should allow for the utilization of heat recovered from the CHP unit's flue gasses for both concurrent (CHP unit and HP unit) and independent operation (HP unit only). For independent operation, the recovered heat is required to be stored.

Key words: *large-scale heat pumps, sustainable energy system design, relocation, techno-economic analysis*

Introduction

Large-scale integration of intermittent renewable energy technologies such as wind power and photovoltaics into existing energy systems represents a major opportunity for increasing energy efficiency, reducing emissions, and optimizing the economic feasibility of the energy system [1-7]. Such development requires innovative solutions in the design and operation of the overall energy system, in particular with respect to providing balancing services in periods of excess power production, maintaining power quality, and increasing the capacity value of small power producers.

In the case of Western Denmark, with 24% of annual electricity demand being supplied by wind power in 2005 and plans for further increasing the share of wind power, measures are being developed for securing a continued efficient and cost-effective integration of grid-connected wind power.

Besides large-scale penetration of wind power, the Danish energy system is furthermore characterized by continued policy strategies to promote system energy efficiency in the form of distributed combined heat and power (CHP) production, which supplied 26% of electricity demand in 2006, while centralized large-scale CHP plants supplied 39% of electricity demand.

Under current operational strategies, such large shares of wind power and CHP are resulting in periods of excess electricity supply. While recorded data may not correspond to the most current projections, fig. 1 illustrates the increasing significance of this challenge as projected by the Danish Energy Authority in 2001 [8].

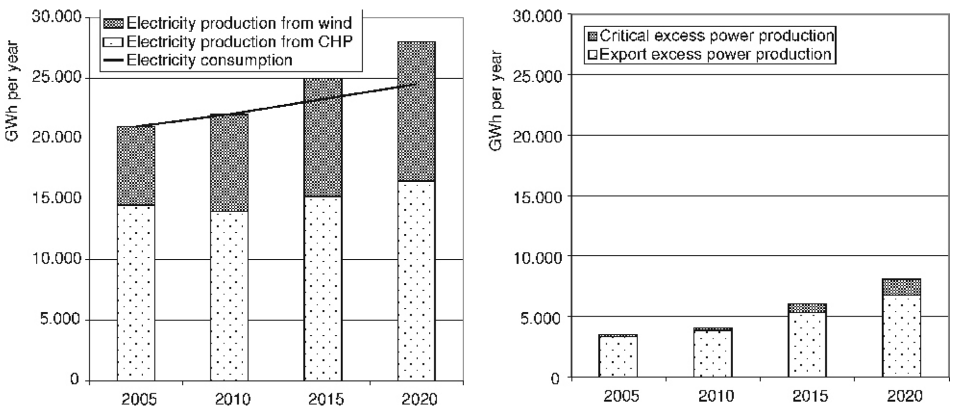

Figure 1. The current and projected share of wind power and CHP-based power generation in Denmark's Western grid (left), and the resulting projected excess power generation (right)

To avoid the foreseen problems in planning for extensive penetration of wind power in Denmark's Western grid, current plans suggests that new wind farms should better target export markets. Such strategy will involve major investments in increasing transmission capacities to neighbouring countries Germany, Norway, and Sweden. Meanwhile, alternative strategies that attempts to assess opportunities for allowing an even larger share of intermittent renewables into the Danish energy system (50% or more of total annual electricity production) may be more cost effective [2]. Such alternative strategies focus on increasing the flexibility of the internal supply and distribution network. Strategies to limit excess electricity production by increasing the closed system flexibility, involves the design of sustainable energy systems which relies on the integration of effective storage and relocation technologies. Figure 2 illustrates the principle by energy system design for the integration of storage and relocation technologies.

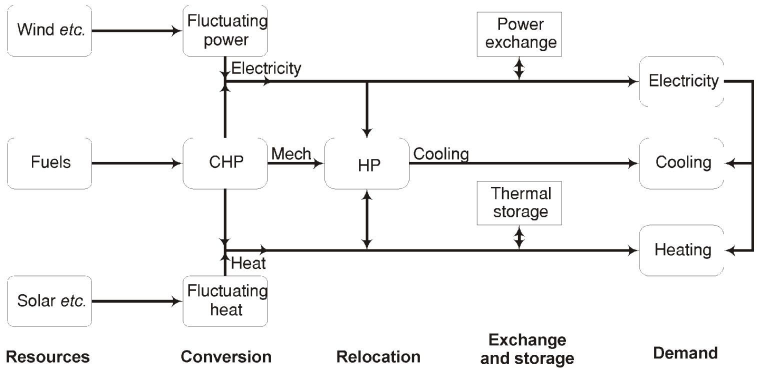

Figure 2. The 2nd generation sustainable energy system (2G) introducing relocation and thermal storage for added operational flexibility

But which storage and relocation options are more feasible from a technical, environmental, economic, and financial perspective? Heat pumps (HP), electric boilers, hydrogen storage, pumped storage? Comparative techno-economic analyses are required in order to assess comparative advantages and disadvantages, and possibly to identify options which could benefit from particular attention by policy makers and project developers.

Lund *et. al* [3] points to one most promising option in a short- to medium-term perspective; the integration of large-scale HP with existing CHP plants. From extensive system analyses for Denmark, Lund finds that the levelized economic benefit in the case of West Denmark amounts to €2.5 mill. per year at current wind power penetration levels. The analysis shows that it will be feasible to integrate a total of 350 MW_e HP, equivalent to the installation of one 1 MW_e HP at the site of the average CHP-plant.

In fact, standard large-scale compression HP are typically available up to about 1 MW_e, equivalent to 3-6 MW heat output, though the integration of HP is likely to be requiring a custom design process [9, 10]. Issues related to ozone-depleting and global warming contributing refrigerants is a problem of the past as CFC and HCFC are being phased out, introducing natural working fluids like CO_2 and H_2O. Findings suggest that natural working fluids are introduced without compromising the coefficient of performance (COP), however it is known that using CO_2 as a working fluid in compression systems generates high pressure differences across the compressor as well as large efficiency losses associated with the throttling process [11]. The Danish Technological Institute is currently collaborating with the Centre for Positive Displacement Compressor Technology to design and demonstrate a technology that balances the rotor forces in twin screw compressors for high pressure applications, thereby significantly improving the efficiency of large-scale HP using CO_2 as the working fluid [12].

A strategy intended to promote the integration of HP suggests the emergence of a new role for distributed power producers in the regulation of supply and demand for electricity. Certain key conditions needs to be taken into account for this purpose; most importantly the communication between the system authority and the individual plant operator and the ability of the plant to react quickly to supply requirements. Research projects indicate that starting and stopping plants currently may take from as little as 10 minutes to as much as 4-6 hours. Furthermore, the ability of distributed producers to supply reactive power would increase the flexibility of the system and allow for the system authority to postpone certain investments in for example condensators [13].

However, in order to establish such new regime and role for distributed producers, regulators will be required to establish new conditions for grid-connection under which investment and operational strategies will be reflecting the economic costs and benefits. In fact, in March 2005, 26 Danish CHP plants offered their combined capacity of 361 MW_e to the transmission grid operator, thereby suggesting a model for how it may become financially attractive for distributed producers to provide regulative capacity [14]. Distributed producers may furthermore provide additional balancing services and operational flexibility by making use of HP for the purpose of taking excess power production in situations of such and generally optimize their operational strategies according to spot market fluctuations.

Objective and methodology

In this paper, it is evaluated whether claimed economic feasibility of system integrated large-scale HP is currently reflected in the market place, *i. e*. whether it is financially feasible under current market conditions for distributed producers to install and operate a large-scale HP.

The analyses are making use of a design and optimization model of a typical CHP-plant with and without HP, on the basis of which a financial cost-benefit analysis is prepared. The energyPRO software [15. 16] is used to model and optimize the simulated operation of the plant over the planning period under given techno-economic constraints. No other proprietary tools are used for this purpose. On the basis of the financially optimized plant operation, the resulting net present value is used as key criteria for assessing the comparative financial feasibility of the options included under the analysis.

Techno-economic assumptions

In the comparative analysis of options for integrating large-scale HP with existing CHP plants, three options are compared (fig. 3):

- Reference: Continued operation of an existing 4 MW_e (3 MW_e + 1 MW_e) natural-gas fired CHP plant with 1,200 m^3 thermal storage (grid-connected, heat used for district heating).
- Option A: Reference plus 1 MW_e HP, for which ground source is used for low-temperature heat source.
- Option B: Reference plus 1 MW_e HP, for which flue gas heat recovery in combination with ground source is used as low-temperature heat source.

For Option A, low-temperature heat is recovered from ground source by a closed system of tubes placed in boreholes or shallow trenches. For Option B, low-temperature heat is recovered from cooling and condensation of flue gasses for concurrent operation of CHP unit and HP, and from ground source in combination with stored heat recovered from flue gasses for independent operation of HP unit (without CHP unit).

All options are optimized according to an operational strategy that allows heating demand at any given hour to be met by the production unit that provides heat at the lowest financial costs, shifting between or combining the CHP unit, the HP unit, and the heat-only boiler, producing to thermal storage whenever feasible.

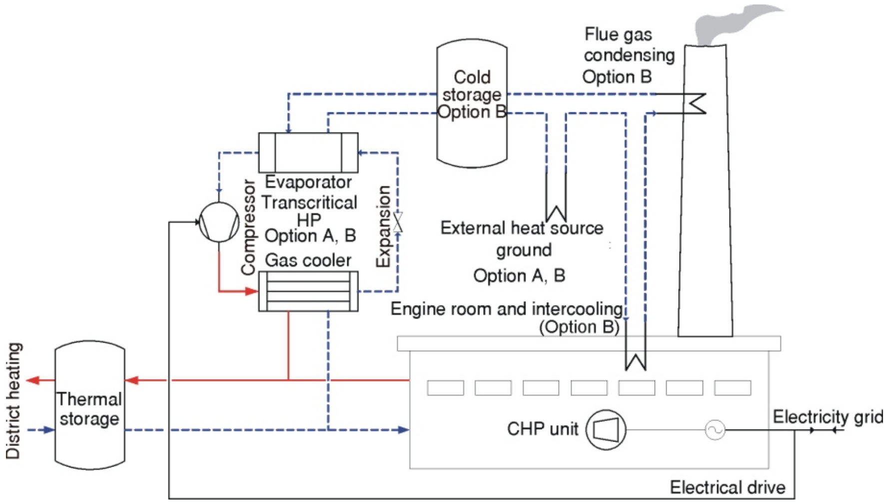

Figure 3. Conceptual plant diagram for options for integrating a large-scale HP with a CHP unit allowing for independent operation of CHP unit and HP unit for operational flexibility by relocation

General assumptions

With 2005 as the first full year of operation, all case options are analyzed over a planning period of 20 years, equivalent to the assumed life time of the HP, furthermore assuming that to be the remaining lifetime of the existing CHP unit; making all investments fully depreciated within the planning period.

A nominal financial discount rate of 15% per year is applied. While this discount rate may seem rather high, it is assumed to mirror well the time preference for new investments among the stakeholders in focus. Current fiscal premiums and taxes are assumed constant in nominal terms. Fixed and variable operational and maintenance (O&M) costs are assumed to increase at the rate of inflation, which is assumed to be 2% per year. A 70/30 debt-equity ratio is assumed, debt being financed over 10 years at 5% per year effective. The results and conclusions are not particular sensitive to these assumptions.

Financial fuel costs and revenues from electricity sales are based on previous year values (March 2004 to February 2005) projected to develop over the planning period at growth rates similar to those projected for economic costs according to planning assumptions suggested by the Danish Energy Authority [17]. The initial natural gas price is based on fixed monthly prices for large consumers [18], and the electricity selling and purchase tariff is based on Nord Pool spot market prices [19]. Electricity purchase taxes for heating purposes apply for electricity used to feed the heat pump.

Case options

Table 1 holds key techno-economic assumptions for the options under analysis. Particular uncertainty relates to the COP of the HP, which is highly sensitive to the temperature levels of the heat source as well as of the heat sink. The average temperature level of the heat source is uncertain due to the various conditions under which the HP will operate. For Option A, the HP will operate on the basis of low-temperature ground source under which conditions the COP may be less than 2, and is unlikely to be higher than 4. An annual average COP of 3.0 is assumed. For Option B, the HP may operate in parallel with the engine-generator, allowing for heat recovery by condensation of flue gasses, which will result in a relatively small temperature lift of the HP, as a result of which a COP of between 3.5 and 5 may be achieved. Heat recovered from flue gasses may be stored for independent operation of the HP, which in combination with using ground source for low-temperature heat source, will allow for an assumed annual average COP of 4.0.

Table 1. Key techno-economic assumptions

	Reference	Option A	Option B
Heating demand			
– Annual supply including grid losses	24.5 GWh		
Installed capacities			
– HP heating	–	3 MW	4 MW
– CHP heating	6.5 MW		
– CHP electric	4.0 MW_e		
Efficiencies (annual average)			
– CHP unit, electric	39%		
– CHP unit, overall	90%		
– Heat-only boiler	95%		
– HP, COP	–	3	4
Investments			
– HP	–	0.7 mill. €	0.9 mill. €
Variable annual O&M costs			
– CHP unit (€/MW_h electric production)	6.5 €/MWh		
– Heat-only boiler (€/MWh heat production)	1.5 €/MWh		
– HP (€/MWh heat production)	–	4.0 €/MWh	4.0 €/MWh

The specific investment cost for large-scale HP is not expected to change towards 2030; however the COP for new HP may be expected to improve by as much as 20% by 2030 without any increases in investment and O&M costs. The potential increase is not considered under this analysis. The technical life time of the HP is assumed to be 20 years at the specified O&M costing levels.

Results

Having established optimized operational strategies under given constraints on an hourly basis for each year of operation, *i. e.* strategies for using available production units for providing heating at lowest financial costs, fig. 4 illustrates the operational profiles for the three options under analysis for a selected week in November 2005.

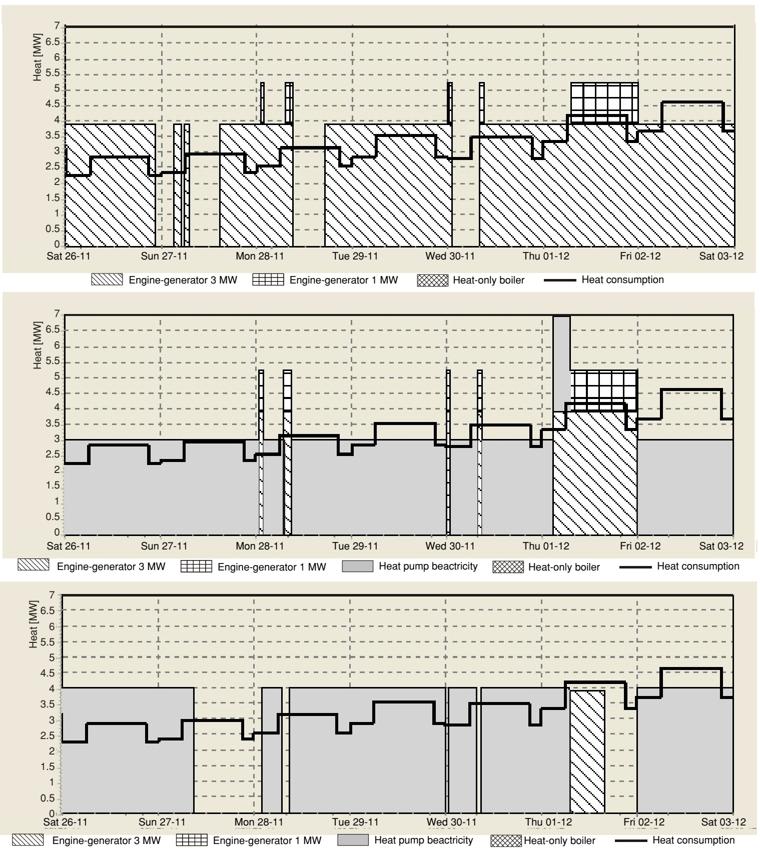

Figure 4. Operation profiles for optimized plant operation
top: reference, middle: option A, bottom: option B

The top figure illustrates the optimal mode of operation for the Reference for this week. It appears that the CHP units are priority production units. The middle figure illustrates Option A's optimal mode of operation, from which appears that the HP unit is the priority production unit for most hours, and generally overtakes the larger share of the heat production from the CHP units. The bottom figure illustrates Options B's optimal mode of operation, from which appears that the HP unit almost completely replaces heat production from the CHP unit.

It appears from a review of the operational profile over an entire year that following the integration of CHP unit and HP unit, the HP unit will significantly overtake heat production from the CHP unit, for Option B more so than for Option A.

Table 2 holds the key financial results for the operation of the three case options. A key criterion for comparison is the net costs of heat production for each option. The financial present values do not include income from heat sales and are thus negative. It is found that Option B supplies heat at the lowest costs under given assumptions. The financial present value for Option B is –5.7 mill. € corresponding to levelized heat production costs of 37.7 € per MWh-heat. In comparison to Reference operation, Option B thereby reduces heat production costs by 8%, while Option A increases heat production costs by 10% from € 41.1 to € 45.7 per MWh-heat.

The results presented in fig. 4 and tab. 2 shows that the integration of a large-scale HP (Option A and Option B) with an existing CHP plant (Reference) may be feasible from a financial perspective, in particular when the option includes heat recovery from flue gasses (Option B). However, a large-scale HP may have significant consequences to the operational strategy of the CHP plant. For example, for Option B, the HP unit almost completely takes over production from the CHP unit, replacing rather than supplementing CHP unit production.

Table 2. Key financial results

	Reference	Option A	Option B
Present value (mill. €)	–6.3	–7.0	–5.7
Levelized production cost (€/MWh-heat)	41.1	45.7	37.7

Conclusions

In conclusion, the results indicate that when a large-scale HP with 50-60% of the CHP unit's heating capacity is integrated with an existing CHP plant under given assumptions, the HP unit almost completely replaces the CHP unit as the financially preferred production unit. However, uncertainties related to the performance of the HP under various operational strategies must be further explored through tests and demonstration projects.

On the financial feasibility including investment costs for HP unit integration, the results indicate that when using only ground source for low-temperature heat source, the overall financial heat production costs increases by about 10% (Option A). A design that allows for the utilization of flue gasses in combination with ground source for low-temperature heat source, a COP increase by 25% combined with a 30% increase in investment costs, results in overall heat production costs being reduced by about 8% (Option B).

The financial results are sensitive to the conditions for grid-connecting distributed producers. The recent move by distributed producers teaming up to supply firm capacity to the grid may add operational benefits to the CHP unit, if rewarded. Another potential impact will be the combination of the increase in electricity demand due to the use of HP and the decrease in electricity produced by the CHP unit, which will affect spot market prices for electricity and thereby benefit the CHP unit relatively over the HP. Analyses will be required in order to assess the feed-back effect on the Nord Pool spot market from the possible increase in demand from HP and the reduced electricity production from the CHP units.

With construction periods of less than 1 year, the integration of large-scale HP with existing distributed producers may be the key to allowing a large share of intermittent renewables into the power grid in the short to medium term. Such integration would help to securing a flexible and cost-effective operation of the energy system, and policy strategies and market conditions should be developed accordingly.

However, the results show that large-scale HP in combination with CHP plants should be introduced with care, not to jeopardize policies to promote co-generation. The integration of a large-scale HP may in some cases almost fully replace existing CHP unit operation, so it is to be considered to which extent large-scale HP should fully replace existing CHP producers, or consider options that limits the heating capacity of the HP to be integrated with the CHP unit. It is indicated that the HP 's heating capacity at given COPs should be much below half of the CHP unit's heat production capacity, estimated to about or less than 15-20% of heat the CHP unit's heating capacity.This would likely be the better option for introducing some system flexibility, while continuing supporting the principle of co-generation.

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The effectiveness of storage and relocation options in renewable energy systems

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Abstract

Across the world, energy planners and transmission system operators are faced with decisions on how to deal with challenges associated with high penetration levels of intermittent energy resources and combined heat and power (CHP). At the same time, distributed plant operators are eager to reduce uncertainties related to fuel and electricity price fluctuations. These interests meet-up for options in distributed supply that introduces the principle of storage and relocation, typically by integrating heat pumps (HP) or electric boilers (EBs) into the operational strategies of existing CHP plants. This paper introduces the principle of storage and relocation by energy system design, and proposes for the storage and relocation potential of a technology option to be found by comparing options by their storage and relocation coefficient R_c, defined as the statistical correlation between net electricity exchange between plant and grid, and the electricity demand minus intermittent renewable electricity production. Detailed operational analyses made for various CHP options within the West Danish energy system, point to the concepts of CHP-HP and CHP-HP cold storage for effectively increasing energy system flexibility. For CHP-HP cold storage, R_c increases from 0.518 to 0.547, while the plant's fuel efficiency increases from 92.0% to 97.2%. These findings are discussed within frameworks of renewable energy systems, suggesting principles for 1st, 2nd, and 3rd generation system designs.

Keywords: Renewable energy system design; Storage and relocation; High penetration levels of intermittent resources and CHP; Large-scale heat pumps; CHP-HP cold storage

1. Introduction

The bright future of intermittent energy resources rests on successfully increasing energy system flexibility. System flexibility may be increased by introducing storage and relocation options such as electrical energy storage facilities [1], pumped hydro storage [2], hydrogen production and storage [3], compressed air energy storage and biomass gasification [4], vehicle-to-grid systems [5], or as in focus of this paper, by integrating large-scale heat pumps (HP) with combined heat and power (CHP) plants. But how are such options compared with respect to technical and economic effectiveness? On the basis of assessments of various CHP concepts [6,7], this paper introduces a method for assessing a technology option's storage and relocation effectiveness, i.e. its effectiveness in providing greater system flexibility. Furthermore a method for assessing the economic cost-effectiveness of these options is introduced.

In support of high penetration levels of intermittent wind power into the energy system, the Danish Ministry of Finance (MoF) recommended in February 2003 that a cost-effective climate strategy for Denmark should be based not only on the continued build-up of wind power capacity, but also the build-up in parallel of large-scale heat pump projects by which system flexibility is introduced. MoF's initial assessments suggested a potential of 1.5 million tons of CO_2 per year from 2012 at an economic CO_2 shadow cost of €-8 per tons of CO_2 for large-scale HP integrated with existing decentralized CHP plants, and 5.0 million tons of CO_2 per year at an economic CO_2 shadow cost of €34 when integrated with existing centralized CHP

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Nomenclature

1G system	1st generation sustainable energy system
2G system	2nd generation sustainable energy system
3G system	3rd generation sustainable energy system
Bt	economic benefits in year t
CHP	combined heat and power
CHP-HP	CHP plant with heat pump
CHP-HP-CS	CHP plant with heat pump and cold storage
COP	coefficient of performance
Ct	economic costs in year t
d	electricity demand minus intermittent renewable energy production (positive for net demand, negative for excess supply)
d_m	mean of d
e	net electricity production (positive for production, negative for consumption)
EB	electric boiler unit
e_m	mean of e
HP	heat pump unit
P_{R_c}	economic R_c shadow cost
quad-generation	combined generation of heat, power, cooling, and liquid or gaseous fuels
r	economic discount rate
R_c	storage and relocation coefficient
R_{c_t}	relocation coefficient in year t
t	year of operation
T	planning period
tri-generation	combined generation of heat, power, and cooling
TSO	transmission system operator
η	plant-level operational fuel to energy efficiency

plants [8], i.e. a combined CO_2 reduction potential of 6.5 million ton per year or about 13% of total CO_2 emissions from Denmark's energy sector in 2002.

The techno-economic appropriateness of a strategy that combines wind power, CHP, and HP, is established by energy system research [9–15], concluding that the introduction of large-scale HP is a feasible option that may effectively be supporting an energy system with fluctuating electricity supply, in particular supporting high penetration levels of CHP and wind power. In 2006, such conclusion is supported for further action by analyses made by the Danish Board of Technology [16] and the Danish Engineering Society [17], and in December 2006, Energinet.dk, the Danish TSO, announced awarding Aalborg University, EMD International, and the Danish Technology Institute €1.5 million for a full-scale demonstration project that will explore further the techno-economic feasibility of integrating a large-scale HP with an existing decentralized CHP plant. The HP is a compression heat pump that uses CO_2 for working fluid in a transcritical cycle allowing for output temperatures that are suitable for district heating purposes.

The integration of large-scale HP with existing CHP plants introduces the principle of relocation into the energy system and provides a means for better balancing distributed generation and wind power. The term "relocation" is used to represent the bridging of energy carriers in 2nd generation renewable energy systems, allowing for advanced optimization of energy system carrier locuses under given constraints. The integration of a large-scale HP with an existing CHP-plant provides a key example of a relocation technology. The availability of a HP enables system operators to opt for a distributed generator to use electricity for heat production, rather than producing electricity due to heat production. The option for producing heat to thermal storage results in de-facto relocation of energy resources without interfering with energy services. The principle of relocation is illustrated in Fig. 6. The paper introduces new metrics for comparing options with respect to their ability to support intermittency.

2. The evolving renewable energy system

While a pre-sustainability energy system is characterized by separating the conventional fuel-based production of heat and power (Fig. 1), a 1st generation renewable energy system (1G) is characterized by the introduction of intermittent resources and co-generation (Fig. 2). For both designs, primary system components may be grouped within four categories: resources, conversion, exchange, and demand.

For a 1G system, intermittent resources and CHP are initially identified by low-capacity factors, i.e. the dispatchable capacity available to the system operator for balancing services is low, if not zero. Grid authorities are well prepared to handle such balancing challenges as these fluctuations show similarities to fluctuations in electricity demand, and for small-scale penetration of wind power and CHP, few practical problems arise and fundamental energy system design modifications are not required. However, for high penetration levels of intermittent producers, it is necessary to increase the operational flexibility of the energy system.

The fundamental problem is that the combination of wind power production and distributed CHP production is basically out-of-sync with electricity demand, or vice versa, and that distributed CHP producers are not able readily to provide the required balancing services due to heat supply constraints.

Fig. 3 illustrates the extent to which wind power production deviates from electricity demand. For 2006, a negative deviation occurs for 6753 h, no deviation occurs for 90 h, while a positive deviation occurs for 1917 h. The

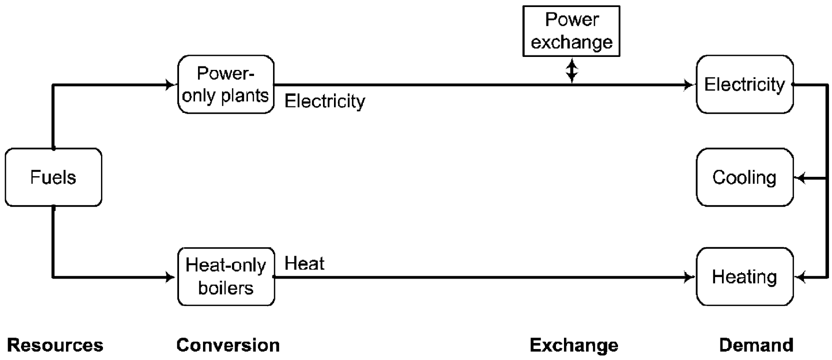


Fig. 1. Pre-sustainability energy system.

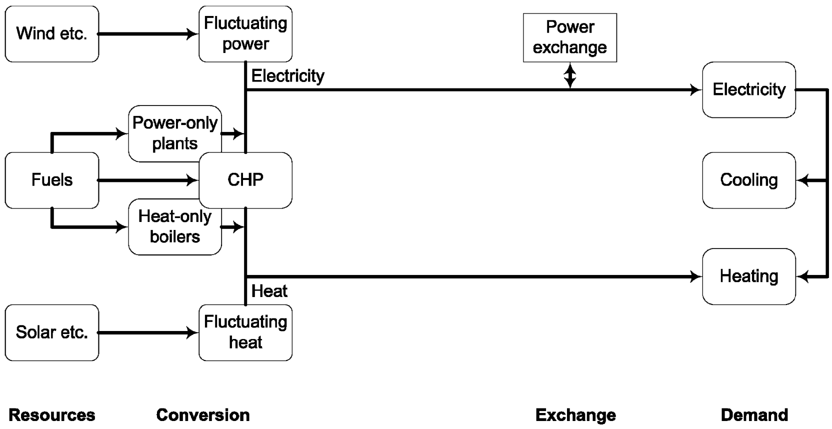


Fig. 2. First generation renewable energy system (1G) introducing intermittent resources and CHP.

overall statistical correlation between electricity demand and wind power production is low at 0.19. The low correlation is not compensated by the typical distributed CHP producer; in fact, the overall statistical correlation between a typical CHP plant's electricity production and electricity demand minus wind power production is 0.518, to be elaborated upon below.

The unreadiness of fluctuating suppliers to provide balancing services contributes to understanding the nature of the serious problem that arose on the night between 31 December 2006 and 1 January 2007 in the Danish electricity system. For the first time, Energinet.dk effectuated an emergency plan to avoid excess electricity production as heavy winds resulted in power production 400 MW above demand and export markets, if unregulated. Initially, Energinet.dk reduced production on large-scale CHP plants according to bids in the down-regulating markets. Subsequently, export capacities to Norway, Germany, and Sweden were fully utilized, and while this was still not sufficient, Energinet.dk requested small-scale CHP plants to stop production. These requests were distributed using personal SMS-messages to plant operators. This latter action reduced power production further by 100 MW, which was still not sufficient and it became necessary for Energinet.dk to force 200 MW of land-based wind turbines to a stand-still for about 10 h. While such emergency plan for critical excess has been in existence for years, this was the very first time that it was executed, indicating that system flexibility is urgently required [18].

Critical techno-economic events and low statistical correlation between fluctuating suppliers and electricity demand are key challenges in a 1G system and something that is deeply embodied in electricity markets. Fig. 4 illustrates that periods of decreasing wind production drives up spot market prices. For example, on Wednesday morning, 10 January 2007, between 6 a.m. and 8 a.m., wind production came close to a weekly minimum, which drove spot market prices to a weekly maximum. Such relationship is also clearly indicated for Monday afternoon, Saturday afternoon, and for mid-day Sunday. Similarly, periods of increasing wind production drive down spot market prices. For example, on Tuesday midday till late evening, high wind production kept spot market prices low during peak demand. This relationship is also clearly indicated for Monday morning, Friday morning, for the

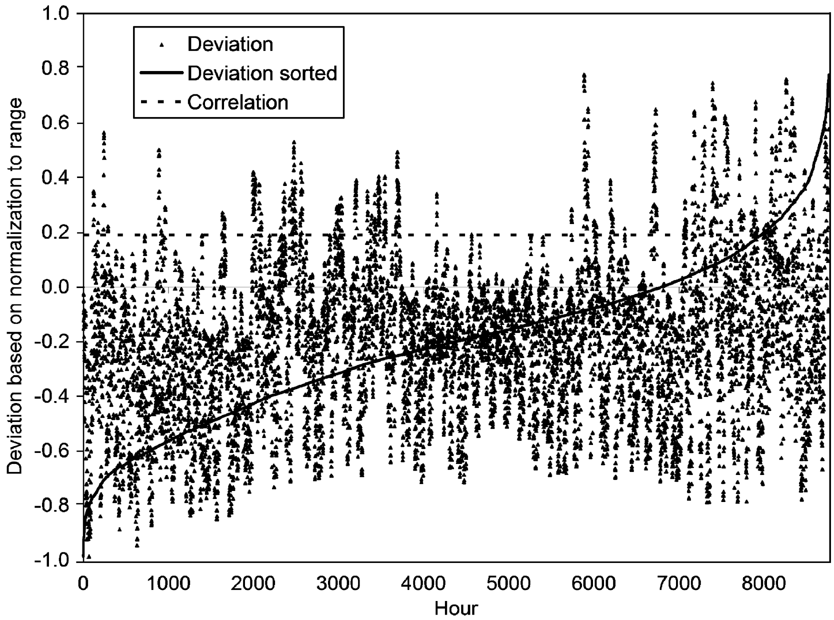


Fig. 3. Hourly deviation between wind power production and electricity demand normalized to maximum values for 2006 in the West Danish electricity system. A negative deviation of −1 says that wind production is at its annual minimum, while electricity demand is at its annual peak. A positive deviation of 1 says that wind production is at its annual maximum, while electricity demand is at its annual minimum.

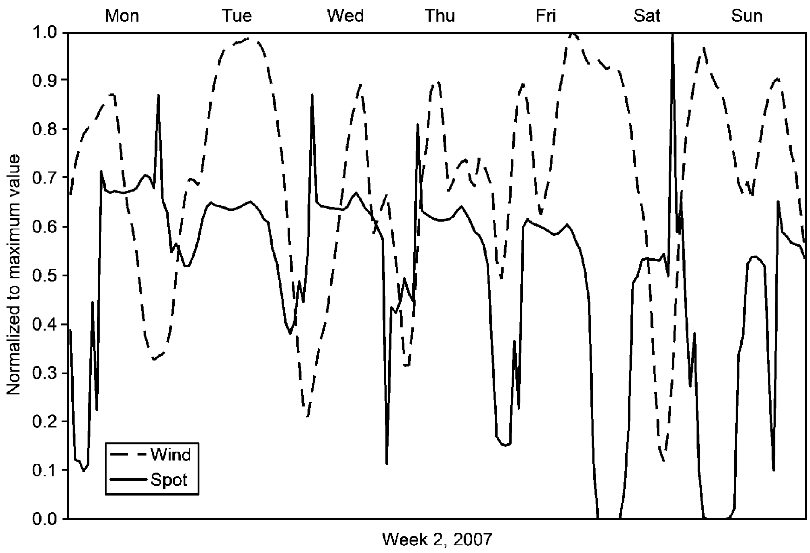


Fig. 4. Normalized spot market prices and wind production for Week 2, 2007.

night between Friday and Saturday, and for the night between Saturday and Sunday. In 2006, the correlation between spot market prices and wind power production was medium at −0.30, indicating that as wind production goes up or down, spot market prices are rather likely to take the opposite direction. Fig. 5 illustrates that spot markets react to wind production as a negative demand. While the correlation coefficient for electricity demand and spot market prices is high at 0.55, indicating that as demand goes up or down, spot market prices are very likely to take a similar direction; the correlation coefficient for electricity demand minus wind production and spot market prices is significantly higher, 0.67 for week 2 in 2007, 0.68 for all of 2006. It appears that electricity demand minus wind production correlates strongly with spot market prices.

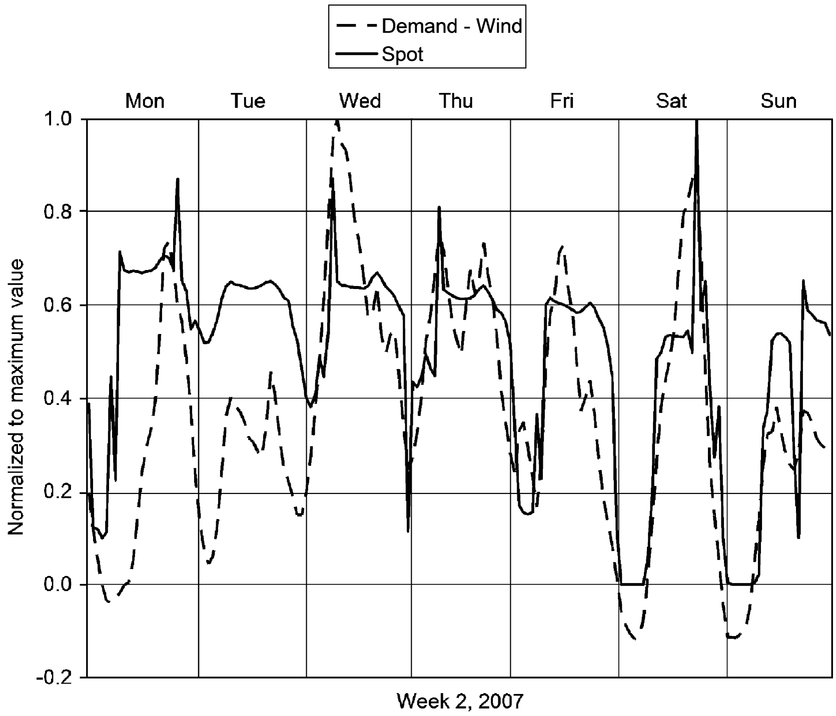


Fig. 5. Normalized spot market prices and electricity demand minus wind production for Week 2, 2007.

The missing flexibility is costly to existing wind turbines owners and is keeping new investors away. When aggregating spot market impacts on an hourly basis for 2006, it appears that Danish wind turbine owners received 8% less for electricity compared to an average producer's income, potentially loosing out on €17 million in annual income from spot market trading. This is partially the reason for the erection of new wind turbines is at a standstill, adding only nine wind turbines (or 12 MW) in 2006, down from 642 MW in 2000 [19].

While off-shore wind farms and new distributed CHP plants are still favoured long-term Danish policy options [20], projections show significant increases in excess electricity supply towards 2015 [21]. This situation is a key policy challenge in the continued move towards renewable energy. What are the options for increasing system flexibility in order to solve balancing problems, while further stimulating the introduction of wind power and CHP?

In 2001, considering various flexible demand options, storage options, infrastructural and interconnection options, the Danish Energy Authority emphasized the cost-effectiveness of introducing thermal storages and large-scale HP to allow for more flexible and system-responsive CHP production modes [22]. This recommendation pointed towards an innovation in renewable energy system design, the principle of relocation, and the 2nd generation renewable energy system (2G).

3. The principle of relocation

A relocation technology introduces flexibility by bridging energy carriers. Fig. 6 illustrates the inclusion of relocation as a fifth system category, introducing the 2G system. An electric boiler (EB) provides simple relocation of electricity to heat. An electric-drive compression HP provides efficient relocation of electricity to both heat and cooling [23].

The conceptual operational modes of relocation for a CHP-HP plant are as follows. In a situation with high wind production, or similar intermittent power generation, spot market prices on electricity drop, stimulating CHP plants to replace co-production of heat and power with purchase of electricity for heat and/or cooling production, possibly producing for thermal storage. The challenge in this situation is maintaining a high coefficient of performance (COP) for the HP. In situations with medium wind production, co-generators and HP may possibly run concurrently, obtaining state-of-the-art plant-level fuel efficiencies in energy conversion for electricity, heat, and cooling. In situations with no wind production, spot market prices on electricity rise, co-generators are stimulated to increase electricity production without HP, minimizing heat production, possibly utilizing stored heat from thermal storage. The challenge in this situation is maintaining high fuel conversion efficiencies.

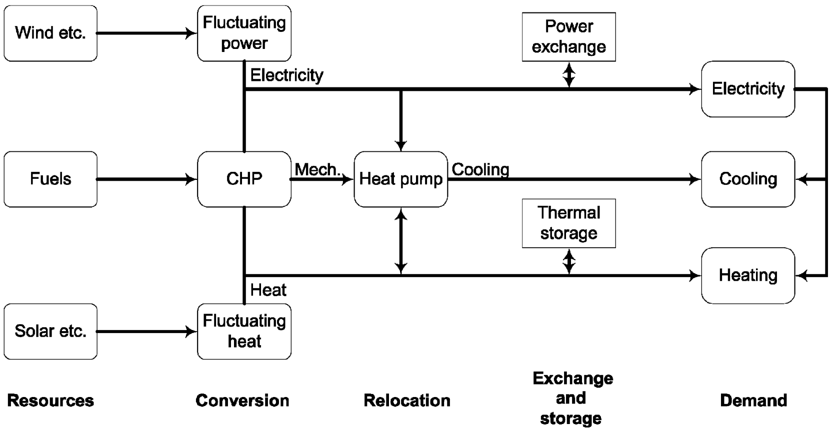


Fig. 6. Second generation renewable energy system (2G) introducing relocation and thermal storage for added operational flexibility.

Integrating an EB or a HP with a distributed CHP plant increases the operational flexibility of the plant, better enabling the delivery of balancing services reflected by electricity markets, including spot markets, upwards and downwards regulating markets, and reserve capacity markets.

4. The relocation coefficient and relocation cost-effectiveness

For the purpose of comparing the potential of storage and relocation options for introducing system flexibility, we will define the storage and relocation coefficient R_c as the statistical correlation between net electricity exchange between plant and system (e), and the electricity demand minus intermittent electricity production (d):

$$R_c = \frac{\sum(e - e_m)(d - d_m)}{\sqrt{\sum(e - e_m)^2 \sum(d - d_m)^2}} \tag{1}$$

The higher the coefficient, the better a plant operates according to system requirements, thereby providing evidence of whether an option supports the introduction of greater system flexibility. As it was previously found that a high statistical correlation exists between spot market prices and minus intermittent electricity production, here wind power, it is indicated that by navigating in spot markets for electricity, coefficients as high as 0.68 for distributed CHP plants may be achieved when operating on market conditions in the West Danish energy system.

For the purpose of assessing the cost-effectiveness of storage and relocation options, we will define the storage and relocation shadow cost P_{R_c} as the economic costs associated with increasing R_c by 1%-point, as given by the economic net present value of a given option compared to the reference divided by the net present value of the change in R_c:

$$P_{R_c} = \frac{\sum_{t=1}^{T}(B_t - C_t)/(1+r)^t}{\sum_{t=1}^{T}(\Delta R_{c_t})/(1+r)^t} \tag{2}$$

The unit of P_{R_c} is € per %-point. P_{R_c} is a useful measure for assessing how a policy objective on increasing system flexibility may be cost-effectively met. A relatively lower P_{R_c} provides evidence of cost-effective options for increasing system flexibility.

5. Coefficients and cost-effectiveness for selected relocation options

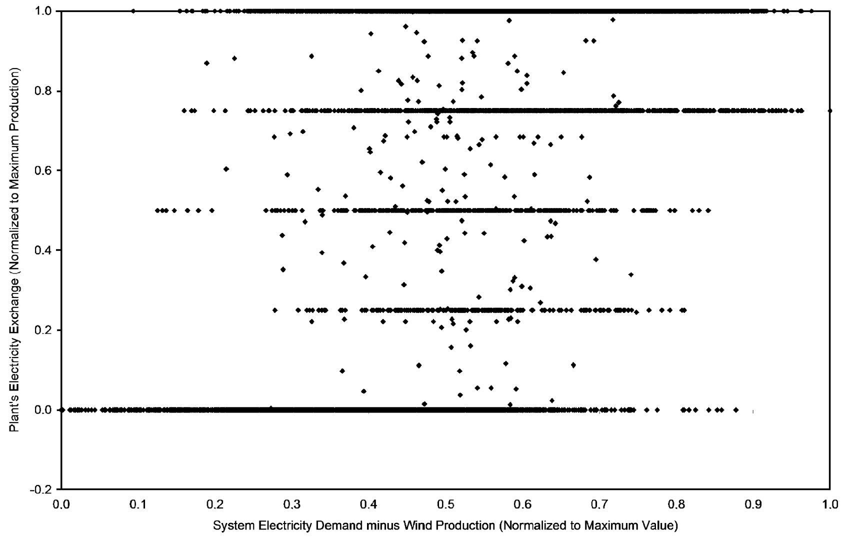
We have compared R_c and P_{R_c} for three CHP options for which operational strategies have been optimized according to economic costs and benefits operating within the context of the 2006 current West Danish energy system and market.

The Reference Option (CHP) is an existing 3.5 MW_e decentralized natural gas fired CHP plant with thermal storage, typical to 25% of the CHP capacity in Denmark, operating on market conditions. Option A (CHP-HP) adds a large-scale electric-drive compression heat pump for utilization of condensed flue gas allowing for the fuel-efficient concurrent operation of CHP unit and HP unit. Option B (CHP-HP-CS) furthermore adds a "cold storage" to allow for the storage of low-temperature heat recovered from condensed flue gasses, thereby allowing for independent operation of CHP unit and HP unit. These innovative CHP-HP concepts are introduced and assessed further by Blarke and co-workers in Refs. [6,7].

The low-temperature heat source for both CHP-HP options is recovered heat from cooling and condensation of flue gasses from 60 to 30 °C. This relatively high-temperature level heat source allows for the HP unit to reach a COP of 3.7 [24]. The HP unit applies a transcritical cycle process using CO_2 as working fluid allowing for delivery temperatures up to 90 °C, which is suitable for district heating delivery or production to thermal storage. For Option A, the HP unit may only be operated concurrently with the CHP unit, but may be disengaged whenever feasible according to operational short-term marginal costs. For Option B, the HP unit may be operated both concurrently and independently of the CHP unit under constraint of a 250 m^3 cold storage.

On the basis of optimized economic operational strategies for each option under given constraints, Fig. 7 illustrates the deviations between selected options' net electricity exchange (selling and buying) and the system's electricity demand minus wind production. We found that R_c increases from 0.518 for the Reference Option to 0.547 for Option B, thereby sustaining that the CHP-HP-CS concept increases system flexibility by allowing the distributed CHP plant to operate in better accordance with fluctuating electricity supply and demand.

As summarized in Table 1, we find that R_c as well as plant-level fuel efficiency η significantly increases by adding a HP, and that the introduction of a cold storage allowing for independent operation of the CHP unit and the HP unit leads to further increases. As levelized economic heat production costs increases by about 5% for both Options A and B compared to the Reference Option, P_{R_c} amounts to €11.4–13.3 million per %-point, lowest for Option B.



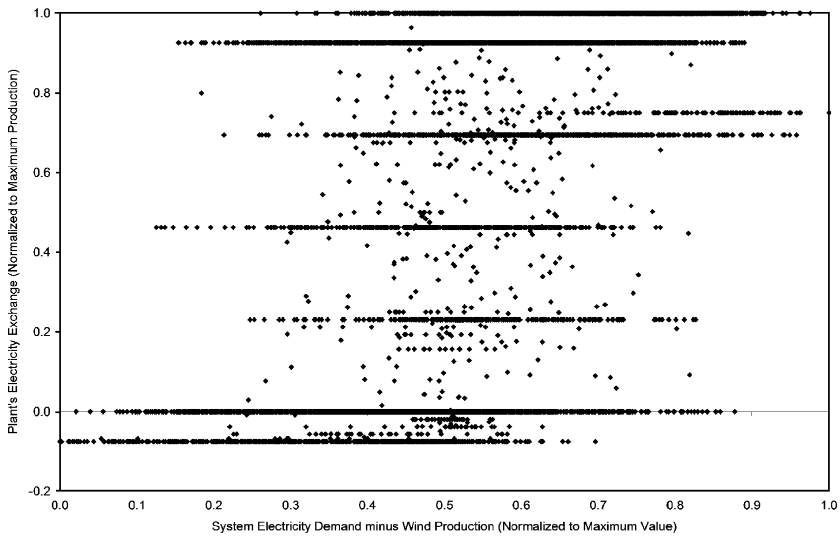


Fig. 7. Hourly deviation between plant's net electricity exchange with system and electricity demand minus wind production. *Top*: Reference Option (CHP). *Bottom*: Option B (CHP-HP-CS).

6. Conclusion and renewable energy system design perspectives

The current 1G energy system with increasing shares of electricity supplied by wind power and CHP poses challenges to TSOs, policy makers, and investors alike, as existing system designs do not sufficiently provide the necessary operational flexibility. In a 2G system, the principle of storage and relocation is introduced by which flexible operational strategies of distributed generators become better synchronized with system requirements. The effectiveness of a particular storage and relocation technology to increase system flexibility is usefully expressed by its storage and relocation coefficient R_c, defined as the statistical correlation between net electricity exchange between relocation technology and system, and the electricity demand minus intermittent renewable energy production. The storage and relocation shadow cost P_{R_c} is useful for identifying the economic cost-effectiveness of thus increasing system flexibility, by relating comparative net costs and benefits to storage and relocation coefficient increases. It is suggested that the proposed methods may assist researchers and policy makers in comparing the effectiveness of storage and relocation options, such as electrical energy storage facilities, pumped hydro storage, hydrogen production and storage, compressed air energy storage and biomass gasification, and vehicle-to-grid systems.

The application of the methods identifies through detailed operational analyses made for selected CHP-HP options the comparative effectiveness of the CHP-HP-CS concept for which a significantly higher relocation coefficient is reached, and more cost-effectively than for the CHP-HP concept.

With respect to renewable energy system design, the 2G system and the principle of storage and relocation is an important step for further renewable energy system developments. In the future, integrated energy systems and increasing levels of flexibility will be reached by incorporating the demand for mobility, as well as the expansion of co-generation or tri-generation into quad-generation, i.e. adding the facility to produce and store secondary fuels, such as hydrogen or ethanol, from primarily fuels, mainly electricity or waste. Fig. 8 illustrates these principles with the framework of the 3rd generation renewable energy system (3G).

Table 1
Plant fuel efficiencies, relocation coefficients and shadow costs for selected CHP options analyzed within the current West Danish energy system

Case	η (%)	R_c	P_{R_c} (million, € per %-point)
Reference option (CHP)	92.0	0.518	–
Option A (CHP-HP)	96.3	0.540	13.3
Option B (CHP-HP-CS)	97.2	0.547	11.4

Acknowledgments

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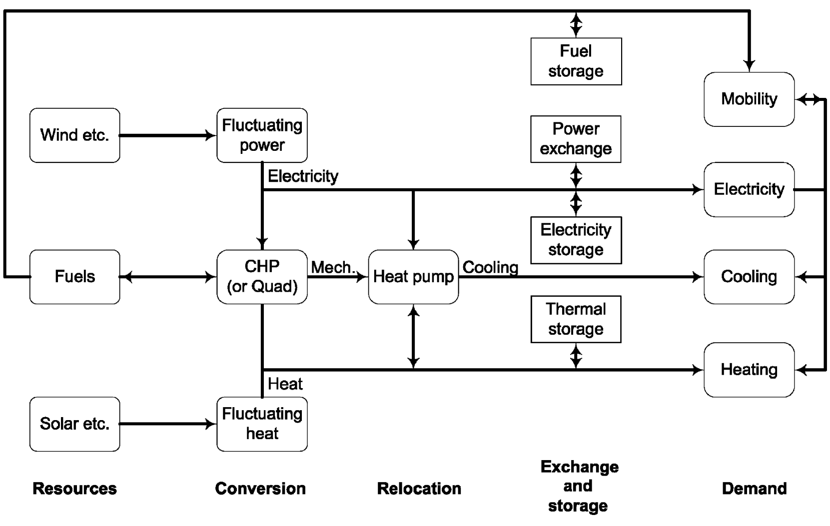

Fig. 8. Third generation renewable energy system (3G) incorporating mobility demand, and introducing electricity storage, and quad-generation for added operational flexibility.

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24

Interactivity in Planning: Frameworking Tools

Morten Boje Blarke

This chapter presents a planning framework which is intended to support interactivity in planning, adding meaning to the term "interactive planning". In particular, the chapter explores the usefulness of developing and applying software tools as a platform for interactivity, while addressing important technical and economic problems.

What do planners do?

In June 2004, under the pretty planned skies of Putrajaya, the administrative capital of Malaysia, the Prime Minister's Economic Planning Unit called for a team of planners to produce a long-term energy plan for Malaysia, the so-called "Malaysia Energy Outlook 2020".

In January 2005, the team's findings were published in the form of an executive policy paper and a number of background reports. The executive policy paper basically discusses what could be priority measures in efforts to promote renewable energy and energy conservation in Malaysia. As such, the paper is an input to the upcoming 5-Year Malaysia Development Plan (2006-2010), which, in Malaysia, is a key policy vector in decision-making.

The policy paper process was another milestone in a programme intended to build capacity in integrated planning research under the Malaysian-Danish programme for environmental cooperation. Activities under the programme began in the late 1990s and are scheduled for completion in 2007.

Without going too much into detail about the particular process, and the successes and failures encountered, it is fair to say that the team of Malaysian, Danish, Dutch, and Australian planning experts covered much ground in efforts to submitting themselves to the particular context.

Early on in the process, in accordance with capacity building principles, much time was spent in dialogue with stakeholders, and the subsequent organization of workgroups and technical workshops took a point of departure in problems already under analysis by stakeholders. For example, one workgroup was established to support the design and construction of a new low-energy office to host the energy administration. Other workgroups were established to support the mapping of local resources, including oil and gas. Again other workgroups were researching particular technical supply options; for example, one group was assessing the problems and opportunities related to large-scale co-firing of coal and biomass at new or existing coal-fired power plants.

For a participating planner, the challenge would be to find ways for dealing with value-based influences in a setting where techno-economic rationality almost completely envelops conflicts. If this is indeed the case, an effective planning framework could be one that submits itself to dealing with ruling techno-economic rationalities, focusing on creating a sober-minded setting for bringing understanding to real conflicts of intent.

While applying the so-called interactive planning framework presented below, it was found that non-proprietary techno-economic planning software was a particularly effective instrument in establishing platforms for interaction between important social interests.

An interactive planning framework

The overall objective of developing an interactive planning framework is to support for democratic goals to rule in planning and decision-making, while promoting interactivity, transparency, and phronesis (Flyvbjerg 2004). Inherently, the framework builds upon the following principles:

- All problems must be taken seriously,
- All goals must be considered respectfully,
- All stakeholders must be acknowledged, and
- All options must be considered on equal terms using standard procedures.

As such, the overall approach builds on principles of various integrated and participatory planning practices, for example Integrated Energy Planning in the early 1980s, which was spearheaded by activists involved in community-oriented energy planning in the third world (Codoni 1986).

Under both integrated and sustainable planning frameworks, the nature of the planning strategy is fundamentally non-technical; focus is on context awareness stressing site-specific knowledge about people, needs, resources, problems, objectives, institutions, and policies. This has unsurprisingly proven to be an effective strategy in planning for a sustainable development, sometimes successfully empowering local communities and governments, supporting lasting changes.

However, the hypothesis is that an intentional focus on the technical and economic rationality resting with stakeholders, combined with the application of non-proprietary software tools that allows for cross-cultural interactive evaluation of options, provides an effective platform for “winners” and “losers” to negotiate better outcomes faster, while avoiding for decisions really to be nothing but reflections of ideological positions and decrees of the powerful.

The framework is intended for planners who strategize to mediate societal interests, while sharing personal experiences, values, and visions.

The big picture

In an interactive planning strategy, appreciation of context is the key to lasting change, and it is useful to distinguish between the external and the internal context.

The external context is the reality into which the planning process is embedded, while the internal context defines the intent of the process.

Using the Malaysian case to exemplify, the external context would be a fast growing Malaysian economy with a growing middle-class oriented towards “modern” needs, the country’s geo-political ambitions, its’ status as an Islamic tiger economy, its’ cultural traditions combining four major ethnic groups, an authoritarian top-down institutional paradigm, an agricultural and industrial infrastructure build on oil and palm-oil, privatization laws in electricity production that favours large-scale producers, as well as more specific influences.

The internal context is the forces that influence the direction of the particular planning process. In the Malaysian case, the internal context was the idea of anchoring analytical planning efforts in the Economic Planning Unit, the agreement between Denmark and Malaysia for Danida to provide technical assistance, the terms of reference and its' appraisal, the client-consultancy schism, the strengths and weaknesses of individual consultants, etc.

From such initial context awareness, the planning team sets out interact with recognized stakeholders and to facilitate interactivity between interests. The process is problem and goal oriented; in fact the planning process is driven by the tension linking problems and goals as they are being expressed by recognized stakeholders. The problem-goal dynamo is the engine that drives the process forward, towards research, evaluations, decisions, and interventions.

The problem-goal dynamo drives the effort to establish an important milestone: a model-oriented description of where we are at and how we got here. We may call this the Reference Situation. For example, this may result in a techno-economic description of the energy system combined with narratives about the origin of it's' elements.

The next step is to consider likely developments, which will result in a model-oriented description of where we are going. We may call this the Reference Scenario. The Reference Scenario helps us better to see the extent of the recognized problems, while enabling us better to understand the dynamics that underlies the problems.

On the basis of the Reference Situation and the Reference Scenario, we will compare and evaluate options. Appreciating that choices have "winners" and "losers", we will put particular emphasis on a transparent breakdown by stakeholder of costs and benefits involved with each option. The notion of costs and benefits should be considered in both monetary and non-monetary terms. The breakdown by stakeholders implies that we will have to evaluate not only socio-economic costs and benefits, but also the costs and benefits for each of the recognized budgets, whether fiscal, community, company, or household.

The identification of consequential winners and losers for each option under evaluation provides information about interests and policies, and becomes an effective basis for fair action, if any.

Figure 1 illustrates this as a circular context-aware process of analysing problems

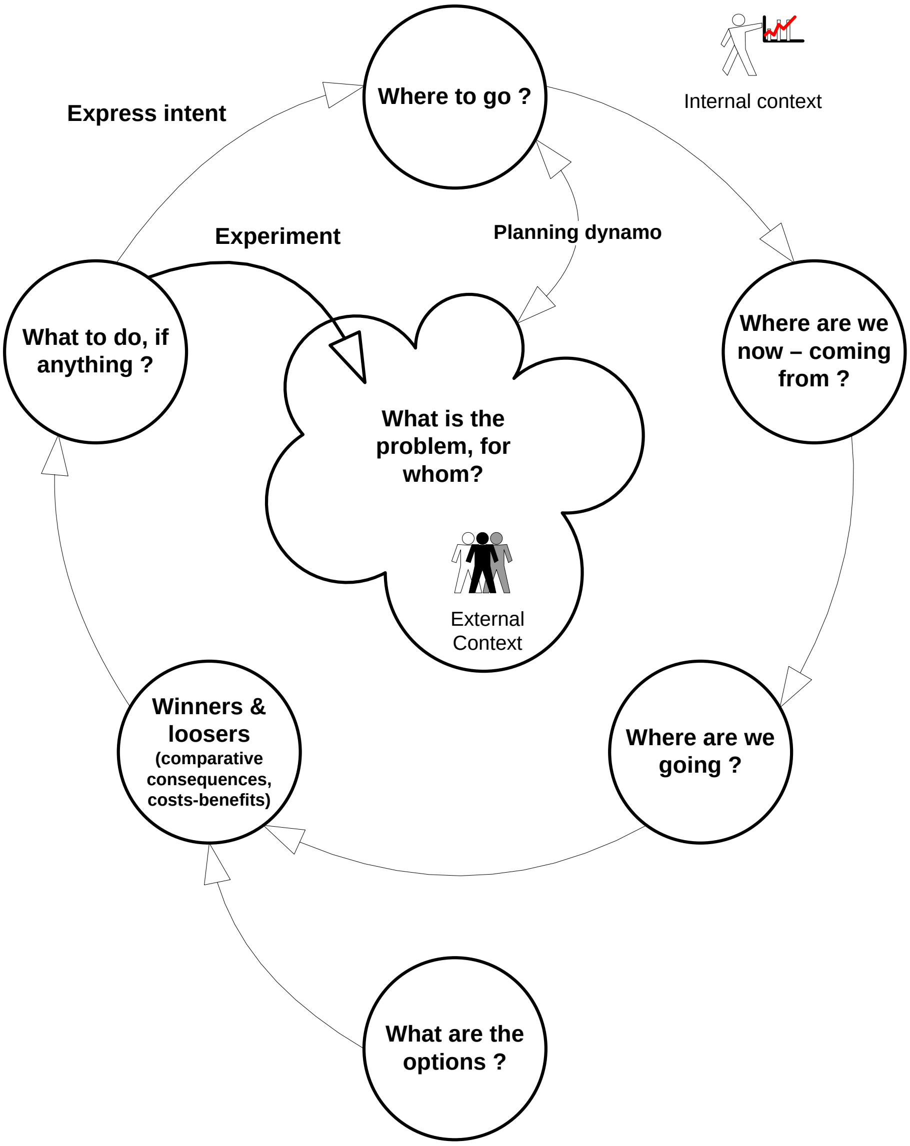

Figure 1: The interactive planning framework.

Through application of various methodologies and tools, the planner will take steps to uncover conflicts of intent, by approaching the technical and economic reality offered by stakeholders.

Step-by-step: methodologies and tools

Table 1 splits the interactive planning process into 7 steps.

Step	Output	Activity
1	External and internal contexts	Explore contexts
2	Problems and goals	Recognize problems and goals
3	Reference situation	Picture current situation
4	Reference scenario	Picture likely development
5	Options	Identify options
6	Winners and losers	Compare consequences
7	Decision and change	Experiment and express policy

Table 1: *Major steps in interactive planning.*

These 7 steps is the basis for suggesting the following partial methodologies and tools.

Step 1. External and internal contexts

Idea – go interactive, get embedded! -

Objective Recognize that the recognition of a problem will stand on an external context (the world) as well as an internal context (your world). Realize that the world consists of nature, people, institutions, culture, technology, and markets, and that any change anywhere will impact this world. Realize that your world consists of location, ethics, skills, terms of reference (if any), even family or partner etc., and that any change anywhere will impact the direction of the process.

Methodology Explore and describe the external and internal context. Go interactive; get embedded for proper anchoring.

Tools Phronetic planning research (Flyvbjerg 2004). Case studies.

Dialogue.

Step 2. Problems and goals

Idea – talk to people first! –

Objective Recognize that societal, economic, and environmental problems are complex and that they origin from fundamental root problems, in particular poverty and population growth. Recognize that the rationality of stakeholders coincides with their interests, and that a democracy deals with conflicting interests. Realize that the tension between problems and goals is a planning process dynamo.

Methodology Identify, describe, and quantify problems and goals vis-à-vis rationalities and interests.

Tools WWW analysis (Hvelplund 1998). Diamond-E analysis (Hvelplund 1998). Action-planning workshops (World Bank 1996). Logical Framework Approach (Danida 1995).

Step 3. Reference situation

Idea – take a snapshot! –

Objective Recognize and frame the current situation with respect to problems and goals, as well as the path followed getting here.

Methodology Take a model-oriented snapshot of significances.

Tools Historical analysis. Statistics and descriptive sector studies. Interviews, document studies, observations. Geographical Information Systems. Techno-economic framework models (for example in energy: LEAP, MARKAL).

Step 4. Reference scenario

Idea – picture a likely future! –

Objective Understand the long-term implication of problems and goal. Expose inconsistencies between goals and the likely future. Realize that projecting, forecasting, and backcasting are different approaches to the future, and to dealing with uncertainty. Seek consensus about the scenario.

Methodology Develop a model-oriented picture of the likely future, call it the Reference Scenario. A typical interpretation is that the Reference Scenario incorporates the effects of what stakeholders agree to expect. The Reference scenario may be based on trends, forecasts, current social and economic policies, business plans, utility demand projections, supply expansion plans, technology learning curves. Consider applying a “Business as Usual” or “Frozen Efficiency” modelling approach, or a combination of these two.

Tools As Step 3, plus Technology Foresight Analysis (Andersen 2001), studies of stakeholder plans and programmes, including the direction of research and development programmes. Seeking consensus about the Reference Scenario requires extensive interaction with and in-between stakeholders, and their vote of confidence in the planning process.

Step 5. Options

Idea – dig deep for options, ask for help! –

Objective Learn that the people, who are experiencing the problems, will lead you to solutions.

Methodology Screen the world for options; new or old, big or small, reform or revolution. Prepare a matrix for comparing option on equal terms.

Tools Real needs analysis. Integrated resource planning. Case studies.

Step 6. Winners and losers

Idea – compare consequences, visualize, and prioritize! –

Objective For each option, identify winners and losers.

Methodology For each option, on equal terms, assess costs and benefits, both monetary and non-monetary, for each and every stakeholder. Consider the fairness. Consider options for compensating losers.

Tools Integrated Resource Planning (Swisher 1997). Life Cycle Analysis. Cost-Benefit Analysis. Strategic Environmental Assessment. Scenario and options evaluation models (for example in energy: LEAP, energyPRO, COMPOSE) that allow for comparative energy, environmental, and economic analyses for projects or programmes in a specific system context. CDM-methodologies (UNFCCC 2005).

Step 7. Decision and change

Idea – project by project, change takes place! –

Objective Recognize that change towards sustainability originates from efforts to put reasoning behind intentions. Recognize that concerting change requires for underlying conflicts to be exposed and managed. Seek power to back your ethics and priorities.

Methodology Preparing and following through on specific projects. Policy formulation. Networking.

Tools Story telling. Demonstration projects. Leadership. Conflict management.

The potential role of frameworking tools

The Malaysian case suggests that the development and application of non-proprietary software tools in the planning process, in this case scenario tools like LEAP and MARKAL, and techno-economic option comparing tools like COMPOSE, potentially may become critical platforms for stakeholder interaction, strongly supporting an interactive planning framework, thus producing the notion of “frameworking tools”.

For example, when discussing electricity generation plans with Malaysia’s electricity supply authority, their generation planning department would rely much on detailed energy systems analyses made with WASP software, thereby using a particular planning software tool to sustain the argument that new coal-fired power plants would be a feasible strategy for Malaysia’s energy sector. As WASP is proprietary tool using confidential and market-sensitive information, it would have been very difficult for most stakeholders to communicate effectively with the electricity supply authority about alternatives.

How to establish an interactive planning process to include this key stakeholder? In the Malaysian case, the introduction of the non-proprietary software tools LEAP, MARKAL, and COMPOSE, turned out to be an effective instrument. Being co-developed by stakeholders, including the electricity supply authority, the software tools became a platform for organising activities relevant under the interactive planning framework.

The software allowed for the technical and economic complexity being experienced by partaking stakeholders to be managed in a cross-professional and cross-institutional setting.

This experience makes it interesting to take a closer look at these software tools, while suggesting some general requirements for planning software to becoming effective frameworking tools in support of an interactive planning process.

System and project tools

In energy planning, and perhaps generally in planning, it is useful to distinguish between tools for system analysis and project analysis (Table 2).

Scope	Description
System	Intends to model the larger system, and for example the relationship between energy, environment and economy, enabling the evaluation of integrated and aggregate scenarios.
Project	Intends to model individual options within a given system.

Table 2: *Main categories of energy planning software tools.*

System tools

LEAP, MARKAL, and ENPEP are classic system tools in energy planning. Their long-lasting success is secured by a growing user base, and the continuous training of researchers, institutions, and governments. Both LEAP and MARKAL was applied in the Malaysian case.

Since 1987, the Long-range Energy Alternatives Planning System (LEAP) has been developed by the Stockholm Environment Institute in Boston, USA. The LEAP model has been applied by "...hundreds of government agencies, NGOs and academic organizations worldwide ... for a variety of tasks including, energy forecasting, greenhouse mitigation analysis, integrated resource planning, production of energy master plans, and energy scenario studies." (LEAP Website 2005). The current online LEAP user forum hosts 1300 members.

LEAP's scenarios are based on the comprehensive accounting of how energy is consumed, converted and produced in a given region or economy under a range of assumptions for population, economy, technology, etc. LEAP's data structure is flexible and allows for an analysis as rich in technological specification and end-use detail as the user may choose.

LEAP stands out as one of the most interesting efforts to build an interactive cross-professional energy planning community for sharing of experiences and visions. The development and success of LEAP give evidence to the hypothesis that tools under an interactive planning framework need to support more than just the ruling paradigm in energy planning – the need to build policies upon a techno-economic or market-economic rationale. To support sustainable development, the tool will need to work well as a playground for interactive communication between stakeholders, and for the organization of technology experiments, learned lessons, and interdisciplinary visions.

MARKAL is being developed under the International Energy Agency programme on Energy Technology Systems Analysis (ETSAP). MARKAL is used for purposes similar to those of LEAP, but applies other principles. While LEAP allows the planner to develop his own techno-economic model, bottom-up, MARKAL uses principles of market-economics and optimization so that it becomes the model that identifies which technologies should be preferred, and the model that provides the ranking as a result. Also MARKAL is widely used; "77 institutions in 37 countries" (MARKAL Website 2005).

ENPEP, which has been developed at Argonne National Laboratories under the auspices of the International Atomic Energy Agency over the past 20 years, uses a combination of techno-economic bottom-up analysis and optimization. According to the developers, ENPEP has been used in training courses reaching an estimated "1200 experts from 87 countries" (ENPEP Website 2005).

The common strength of LEAP, MARKAL and ENPEP is that these models are model building tools rather than rigid models, which allow for partaking planners to develop customized frameworks at various aggregation levels and for various locations.

In 1999, researchers at Aalborg University began developing the EnergyPLAN model to allow for a rather aggregate, but detailed hour-by-hour simulation of an electricity system, enabling the analysis of large-scale penetration for intermittent production technologies, mainly wind power. As of now, the EnergyPLAN model is used in-house and by some partners.

From studying these models, it appears that the energy planning community distinguishes particularly between principles of engineering-economics and macro-economics, thereby also reflecting fundamentally different academic traditions of analysis in-between engineers and economists. Furthermore, it appears that plans for any large-scale penetration of intermittent production technologies, like wind power or photovoltaics, call for advanced system simulations, a requirement which is currently not met by the most widely used energy system models (though the ENPEP modelling environment internalizes the use of WASP that simulates the electricity generation system in great detail).

Table 3 provides a comparative overview of these and other significant system models. Certainly, countless models have been excluded, though many are still available to the research community. But more often than not, these models have disappeared due to insufficient support and a weak user community – or they are only available in-house, sometimes only being developed and used by a single researcher.

Tool	Scope	Methodology	Developer
LEAP	Integrated energy/environment analysis	Accounting	Stockholm Environment Institute – Boston.
MARKAL	Integrated energy/environment analysis	Optimization, Equilibrium	International Energy Agency's Energy Technology Systems Analysis Programme.
ENPEP	Suite of model for integrated energy/ environment analysis	Various	Argonne National Laboratory for the International Atomic Energy Agency.
WASP	Long-term electricity generation planning including environment analysis	Optimization	International Atomic Energy Agency.
PRIMES	Integrated energy/environment analysis	Partial equilibrium	National Technical University of Athens.

	for EU-25		
EnergyPLAN	Large-scale intermittent electricity supply systems	Simulation	Aalborg University.

Table 3: *Selected system tools in energy planning.*

Project tools

Project analysis has traditionally been, and is still often handled by ad-hoc models, typical spreadsheets, that cater only for a specific project, for example using techno-economics to analyse a combined heat and power plant. In terms of producing an energy balance or a simple cash-flow, ad-hoc models are often an effective way to go about evaluating a single project.

However, even for single project evaluations growing complexities in control strategies and system integration are pushing for standardization. When several projects – often different in nature – need to be compared on more than simple financial criteria, more advanced modelling principles are required. And in an interactive planning process, the project tool should also support and record the learning process, which ad-hoc models cannot always do (unless organized as a participatory development from scratch).

RETScreen, energyPRO, and COMPOSE, are model suites which have been developed to allow for consistent and comparative project evaluations under specified system constraints and control strategies.

RETScreen is a suite of tools developed and distributed by the Institute of National Resources, Canada, enjoying the financial and technical support of NASA, UNEP, and GEF. RETScreen software combines the principles of technology-specific spreadsheets with a common user-interface and database, and allows the user to produce a financial cost-benefit analysis for a particular energy project, such as wind turbines, small hydro, photovoltaics, combined heat and power plants, and solar heating. RETScreen boasts an incredible “64,283 users in 207 countries” (RETSCREEN Website 2005).

Since 1986, EMD International has been developing the energyPRO software for commercial applications in design, optimization, and evaluation of advanced combined heat and power plants. Today, energyPRO is a recognized industry standard in Denmark and Germany, and is widely used in many parts of Europe by engineers, project developers, and plant managers.

Since 1999, COMPOSE has been developed by this author for externality-oriented techno-economic energy project analysis that offers cost-benefit and cost-effectiveness analyses based on a wide range of important benefits and costs - energy resources, environment, economic costs, financial costs, employment, balance of payment, fiscal costs. COMPOSE has a solid institutional user base in Malaysia, and is furthermore used by a few Danish energy consultancies as a platform for project analysis and capacity building in energy.

The major differences between these models are their scope in terms of which feasibility criteria are included in the analysis, as well as their abilities to compare demand-side and supply-side technologies.

Table 4 provides a comparative overview of these modelling tools.

Tool	Scope	Methodology	Developer
RETScreen	Financial costs-benefit analyses of individual technologies	Database and techno-economic energy project analysis	CANMET Energy Technology Centre.
energyPRO	Simulation of advanced CHP projects, financial cost-benefit analysis	Simulation and optimization according to market constraints	Energy and Environmental Data.
COMPOSE	Externality-oriented comparative assessment of demand-side and supply-side options	Database and techno-economic energy project analysis including economic costs, employment, balance of payment, fiscal costs.	Aalborg University

Table 4: *Selected project tools in energy planning.*

Requirement specifications for frameworking tools supporting interactivity

This chapter has discussed the concept of a planning framework that emphasizes the importance of interactivity within context, relying on a platform of sober-minded techno-economic analysis. In supporting this framework, the potential usefulness of certain modelling tools is suggested, hence introducing the notion of “frameworking tools”.

In conclusion, the framework and toolbox may be identified or developed under a set of general requirement specifications. Textbox 1 lists ten requirements for a software tool to be supporting interactivity in planning:

1) Builds on context embeddedness.
2) Stimulates learning and enables the reuse of previously learnt material.
3) Is open and inclusive towards stakeholders and disciplines.
4) Engages the values and interests behind the identified problems and goals.
5) Uses the recognition of problems and goals to formulate the criteria against which to compare options.
6) Is accurate in addressing technical and economic problems experienced by stakeholders, allowing for identifying winners and losers.
7) Complements or replaces proprietary methodologies and tools.
8) Allows for a transparent and uniform evaluation of alternatives with respect to the feasibility criteria as derived from recognized problems and goals.
9) Allows for the visualization of visions.
10) Enables cross-cultural exchange of stories and data.

Textbox 1: *Ten requirements for a software tool to be supporting interactivity in planning.*

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Technical and economic effectiveness of large-scale compression heat pumps and electric boilers in energy systems with high penetration levels of wind power and CHP

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Abstract

High penetration levels of intermittent energy resources and combined heat and power (CHP) plants require innovations with respect to storage and relocation, i.e. system flexibility by storing energy or by bridging energy carriers. This paper introduces a techno-economic modelling framework and case-study for options that increases the ability of a CHP plant to provide system flexibility. From detailed operational analyses of concepts for adding heat pumps (HP) or electric boilers (EB) to CHP plants, the storage and relocation coefficient, defined as the statistical correlation between the plant's net electricity delivery and electricity demand minus intermittent production, is used to assess the relocation effectiveness of options. A relocation shadow cost is used to evaluate the economic cost-effectiveness of options. It is found that an innovative CHP-HP Cold Storage concept that stores heat recovered from flue gasses allowing for independent HP unit operation is an effective option for allowing distributed CHP plants to support high penetration levels of wind power and CHP. Applying a system-wide impact perspective, it is found that concurrent operation of CHP unit and HP unit should be disallowed as reductions in net electricity delivery from the CHP plant jeopardizes system-wide fuel and environmental efficiency.

Keywords: Renewable energy systems; storage and relocation; large-scale transcritical compression heat pumps; CHP-HP Cold Storage; Monte Carlo techno-economic risk analysis.

Nomenclature

CHP	Combined heat and power
CHP-EB	CHP plant with electric boiler
CHP-HP	CHP plant with heat pump
CHP-HP-CS	CHP plant with heat pump and Cold Storage
CHP-HP-GS	CHP plant with heat pump and Ground Source
COP	Coefficient of performance
CS	Cold Storage

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EB	Electric boiler unit
GE1,2,3,4	Gas engine 1, 2, 3, or 4.
GE-HP1,2,3,4	Gas engine and HP unit in concurrent operation 1, 2, 3, or 4.
HP	Heat pump unit
IRR	Economic internal rate of return
kWe, MWe	Electric capacity
O&M	Operation and maintenance costs excluding fuel costs
Rc	Storage and relocation coefficient
TSO	Transmission System Operator

1. Introduction

Across the world, energy planners and transmission system operators are increasingly faced with decisions on how to deal with challenges associated with high penetration levels of intermittent energy resources as well as distributed CHP plants [1,2,3,4,5,6,7].

In Denmark, a 1st generation renewable energy system has evolved by incremental integration of distributed CHP plants and wind power. In 2005, distributed CHP plants and wind power supplied 26% and 24% of annual electricity demand in the West Danish grid. Such penetration levels are contributing to market volatility, while increasingly posing technical and economic challenges to the TSO. In result, the penetration of distributed CHP plants and wind power is at a stand-still, jeopardizing policies further to reduce negative economic and environmental impacts from the energy sector.

The solution is to increase the flexibility of the energy system by increasing its' ability to manage fluctuations and intermittency. Recent policy measures aimed at increasing system flexibility have been gradually to force distributed power producers to operate on market conditions. By January 2005, all Danish CHP plants above 10 MWe (49 plants, 1.220 MWe) had moved away from fixed tariffs to market conditions (spot market, regulating market). By January 2007, all Danish CHP plants above 5 MWe (an additional 74 plants, 438 MWe) were moved to operate on market conditions. Thereby 144 plants are now operating on market conditions, representing about 75% of total electricity generating CHP capacity. All plants below 5 MWe (684 plants, 713 MWe) may continue on triple tariffs until 2015.

Whether operating on market conditions or triple tariffs, thermal storages have long been part of the typical CHP plant's operational strategy allowing for some operational flexibility and the utilization of existing thermal storages by plants now operating on market conditions have solved some of the immediate problems with respect to excess electricity production and market fluctuations, but not sufficiently to allow for further penetration of CHP and wind power.

One key principle for introducing additional system flexibility is the principle of storage and relocation by which energy carriers are stored or bridged, introducing the 2nd generation renewable energy system [8,9]. Various options exists for increasing system flexibility such as electrical energy storage facilities [10], pumped hydro storage [11], hydrogen production and storage [12], compressed air energy storage and biomass gasification [13], vehicle-to-grid systems [14], or, in focus with this paper, the use of electricity for heat production replacing CHP-based electricity production in periods of high wind power production.

For the policy maker, relocation technologies allows for greater penetration rates for distributed CHP plants and intermittent electricity supply such as wind power, and may result in higher system efficiency, improved system flexibility, reduced fossil fuel consumption, and reduced environmental impacts. For the plant operator, relocation technologies will reduce the impact of uncertainty by adding operational flexibility and electricity as a new fuel for producing heat.

This paper introduces concepts that increase the relocation potential of existing CHP plants by operational integration of large-scale compression heat pumps or electric boilers. In this respect, a methodological framework is introduced for evaluating storage and relocation options with respect to operational strategies, potential for increasing system flexibility, cost-effective relocation, and techno-economic risks.

2. Relocation concepts under analysis

Four relocation concepts that introduces electricity as "fuel" for producing heat at an existing CHP plant are introduced; CHP-EB, CHP-HP, CHP-HP Cold Storage, and CHP-HP Ground Source. Schematics for options under analysis are illustrated in Fig. 1.

The CHP-EB concept adds an electric boiler (EB) to an existing CHP plant, enabling the plant to use electricity to produce heat for delivery or storage.

The CHP-HP concept adds an electrical or mechanical compression heat pump (HP) to an existing CHP plant, using flue gas cooling, and/or intercooling, as the only low-temperature heat source, allowing for concurrent operation of CHP unit and heat pump. No external low-temperature heat source is established and only concurrent operation of CHP unit and heat pump is therefore possible. For concurrent operation, the plant's heat production capacity increases by 15% – 20% compared to CHP unit production alone depending on Cm-values, while net delivered electricity is reduced by up to 10%. The capacity of the compression heat pump is designed under constraint of the heat available for recovery from cooling and condensation of flue gasses.

The CHP-HP Cold Storage concept adds an electrical compression heat pump and a thermal storage (Cold Storage) to an existing CHP plant. The Cold Storage stores low-temperature heat recovered from low-pressure cooling and condensation of flue gasses whenever the CHP unit is in operation. When the heat pump operates, it generates cold water for subsequent low-pressure cooling and condensing of flue gasses, in the case study from 60°C to 30°C. The Cold Storage handles these temperature levels ranging from 20°C in the bottom of the storage tank to 60°C in the top. As such, the Cold Storage is operated as an integrated heat source, allowing for high-efficiency operation of the heat pump without concurrent operation of the CHP unit. The CHP unit and the heat pump may in principle also be operated concurrently.

The CHP-HP Ground Source concept adds an electrical compression heat pump to an existing CHP plant, using ground source for low-temperature heat source, enabling the plant to use electricity to produce heat for delivery or storage. Using ground source for low-temperature heat source allows for fully independent operation of the heat pump. The CHP unit and the heat pump may in principle also be operated concurrently.

3. Transcritical CO2 heat pump technology

For CHP-HP Cold Storage and CHP-HP Ground Source concepts, the operation of the heat pump without concurrent operation of the CHP unit and without supplementary boiler operation is made possible using a transcritical cycle reaching exit temperatures of up to 90°C at design COP, suitable for district heating grid delivery or production for thermal storage. While only concurrent operation is modelled for the CHP-HP concept, in principle allowing for an intermediate heat pump delivery temperature, a transcritical cycle is also applied here for analytical consistency.

Design, modelling, and laboratory testing of a transcritical CHP-HP concept with mechanical drive of a compression heat pump has been undertaken by the Danish Technological Institute. After a thorough evaluation of heat pumps alternatives, including absorption heat pumps and options for using NH3 as working fluid, it is concluded that a large-scale transcritical heat pump using CO2 as working liquid is likely to be the most feasible option for future integration with CHP plants producing district heating [15]. The attractiveness of features related to the use of CO2 as working fluid for heat pumps is supported by further research [16,17,18].

Important research questions covered by the laboratory unit tested relates to whether sufficient temperature levels are reached at given operational pressures, as well as to the practical COPs reached at design pressure and temperature levels. For the initial design of CHP-HP, the heat pump was designed for the purpose of heating water from 40°C to 80°C. For this purpose, the compressor's discharge pressure and the gas cooler was designed for 115 bar / 90°C. For the purpose of flue gas cooling and condensation, the working liquid is expanded back to 57 bar / 20°C in the evaporator. The laboratory tests showed that an exit temperature of 90°C was in fact reached for a discharge pressure of 115 bar. However, the expected design COP of 3,7 was not reached. As shown by Sarkar [19], the COP of the heat pump is a function of inlet temperature to the evaporator, inlet temperature of heat sink, as well as compressor speed and discharge pressure. However, in praxis, heat losses, pressure losses, and an isentropic compressor efficiency lower than expected by the manufacturer, may help to explain a resulting lower practical COP. The practical COP for the laboratory unit was 3,2, but after evaluating likely reasons for the lower practical COP a practical COP of 3,7-3,8 is expected for a full-scale plant [15].

Reaching such state-of-the-art COPs for exit temperatures up to 90°C is made possible by using a relatively high temperature level heat source, namely cooling and condensation of the CHP unit's flue gasses. When using ground source for low-temperature heat source, it is estimated that the annual average COP will be from 2,0 to 2,5. While few recent experimental results relates to such option for large-scale applications, it is possible that high exit temperatures are not reached in praxis for low temperature level heat source due to critically high pressure differences.

With these uncertainties in mind, the transcritical CO2 heat pump, characterised by state-of-the art COPs at high exit temperature levels suitable for district heating delivery or, which is important with respect to effective relocation, the production to thermal storage, is investigated for use with the included concepts; CHP-HP, CHP-HP Ground Source, and CHP-HP Cold Storage.

4. Methodology and assumptions

Detailed operational and techno-economic models have been developed for a case study typical to 25% of the CHP capacity in Denmark, i.e. CHP plants under 5 MWe.

The operational optimization models were developed for each option using EnergyPRO modelling software from EMD International A/S. EnergyPRO is a referenced tool for the design, simulation and optimization of co-generation projects [20,21,22,23]. The techno-economic analysis including Monte Carlo risk simulations applies authors' own modelling software.

4.1. Approach and methodology

Existing CHP plant operation (Reference) is compared to two options for which concurrent operation of CHP unit and HP is allowed: CHP-HP (Option A) and CHP-HP Cold Storage (Option B). Furthermore, the Reference is compared to four options for which concurrent operation of CHP unit and HP is disallowed: CHP-HP Cold Storage (Option C), CHP-HP Ground Source with HP electricity consumption capacity similar to that of Option A, B, and C (Option D), CHP-HP Ground Source with HP heating capacity similar to that of the CHP unit (Option E), and CHP-EB (Option F). Schematics for options under analysis are illustrated in Fig. 1.

The options are compared with respect to key system-wide techno-economic impacts: fossil energy resource consumption, CO2 emissions, levelized economic production costs of heat, and relocation potential and cost-effectiveness.

The operational strategy for each option is optimized according to lowest economic costs of heat production on an hourly basis for each year of operation. The optimization takes place according to perfect navigation in the spot market for electricity under specified techno-economic constraints, using economic factor prices (i.e. spot market prices plus transportation and handling costs, internalizing CO2 emission costs, but excluding taxes and subsidies, if any). Investment costs, O&M costs, and fuel costs are based on economic factor prices excluding taxes and subsidies, if any.

Furthermore, a Monte Carlo risk analysis by which a large sample of scenarios are analysed under specified uncertainty ranges with respect to key assumptions, is used to evaluate the robustness of conclusions.

The assessment applies a socio-economic impact perspective and does not directly address an option's financial viability. Methodology and key assumptions are sought to be closely in accordance with those provided by the Danish Energy Authority for comparing energy sector options [24].

4.2. General assumptions

The planning period is 20 years (2006-2025) and a real discount rate of 6% p.a. is used when discounting future values.

4.3. Case study assumptions

The assessment applies a case study approach looking at an existing CHP plant situated in West Denmark. Today, the plant operates four 870 kWe Caterpillar gas-engines as well as supplementary boilers. The annual district heating supply amounts to 38.675 MWh with monthly and daily distribution curves based on 2005 recordings, and the gas-engines operate with a annual average net electrical efficiency of 33,2 % and a overall efficiency of 91,8 %. Supplementary 15,1 MWq natural gas boilers are operated at an annual average efficiency of 93,0 %. Optimized market operation of the gas engines is supported by an existing thermal storage of 865 m3 that holds 36,1 MWh at a design temperature range of 90°C to 50°C. Each engine is assumed to be out for maintenance one week per year during the space heating season.

By stoichiometric analysis on the basis of on-site measurements it is found that 698 kW of heat may be recovered from flue gasses by further cooling and condensation from the existing flue gas temperature of 60°C down to 30°C. With a COP of 3,7, the utilization of this source allows for the integration of a 258 kWe CO2 heat pump with a heat production capacity of 956 kWq.

Total investment costs for integrating a transcritical CO2 compression heat pump with a practical COP of 3,7 and a Cold Storage at an existing CHP plant is highly site specific. For the case under investigation, total investment costs are found to be €0,58 mill. for CHP-HP (Option A), €0,67 mill. for CHP-HP Cold Storage (250 m3) (Option B and C), €0,43 mill. for CHP-HP Ground Source with limited heating capacity including heat absorbers (Option D), €4,7 mill. for CHP-HP Ground Source with full heating capacity including heat absorbers (Option E), and €0,67 mill. for CHP-EB (Option F). Option A's break-down of investment costs is representative: HP unit 62%, Cold Storage tank 14%, stack modifications 10%, optional low-pressure heat exchanger modifications 14%. For ground-source options, heat source investments are €6,7 per m at 30 W per m. For the electric boiler options investment costs amount to €107 per kWe.

O&M costs excluding fuel and electricity costs are based on existing service contracts assumed to relate only to net delivered electricity, estimated at €10,7 per MWh electricity delivered.

For existing equipment and new investments, the lifetime is expected to be 20 years.

4.4. Fuel and electricity price assumptions

Fuel and electricity price assumptions in accordance with those suggested by the Danish Energy Authority [25] in combination with the current economic fuel price projections provided by the International Energy Agency [26]. The average unweighed economic electricity price including transmission and handling costs for each year in the planning period is given by projections made by the Danish Energy Authority. Hourly fluctuations in electricity prices for all years are given by spot market fluctuations in the Nordic Power Exchange (Nord Pool) for West Denmark recorded for 2006 [27].

Changes, if any, in capacity payments, fees to Nord Pool, and trading fees are ignored. Electricity grid distribution costs amounting to €14,1 per MWh are applied for operating hours that result in net purchase of electricity, reflecting that distribution costs are held by the end-user. Distribution costs are not applied for operating hours where net delivery of electricity occurs, as this simply is reflected by reduced electricity production.

Electricity is exchanged at medium voltage levels (10kV) assuming a grid efficiency of 94 %.

4.5. Marginal fuel consumption and emissions in central electricity generation

The assessment applies a system-wide perspective and internalizes any consequences from the plant influencing electricity production elsewhere in central electricity generation. While the economic costs and benefits of changes in central electricity generation are given for each operating hour according to electricity price assumptions, the issue of how to handle marginal resource consumption and CO_2 emissions needs further clarification.

According to the Danish Energy Authority, a projected economic cost of €20 per ton of CO_2 constant in real terms is currently used for evaluating energy options. This assumption is based on the current long-term projection for quota costs under the evolving CO_2 trading system. As CO_2 emissions in the electricity system is largely already subject to CO_2 quotas, actual and projected spot market prices are already internalizing the economic costs of fulfilling these quotas. Therefore it is argued that no marginal economic CO_2 cost is associated with a distributed producer's electricity production or demand. The question is whether the inclusion of marginal CO_2 emission costs and benefits related to changes in the CHP plant's supply-demand patterns would be double-counting these costs and benefits?

We will argue that the options under analysis are marginal to current plans for reducing CO_2 emissions in central electricity generation and that it is reasonable to apply a marginal emission costing perspective. This argument is strengthened by the potential impact these options may have on CO_2 emission reduction potentials by means of allowing for greater penetration levels of wind power and CHP, allowing for reducing quotas, or even that quotas may voluntarily be discarded. We therefore propose that the marginal inclusion of costs and benefits from marginal CO_2 emissions in central electricity generation is the appropriate methodology for assessing the economic feasibility of storage and relocation options.

As such, the problem is to identify marginal CO_2 emissions in central electricity generation, which is complicated by the basic challenge of identifying the marginal production technology and associated emissions in central electricity generation for each hour of operation. However, from the reasonable assumption that operators seeks to react to fluctuations by dispatching according to lowest marginal production costs under given technical and environmental constraints, we will expect for the marginal production technology to correlate with marginal production costs.

Assuming that marginal fuel consumption and emissions is a function of spot market prices for each hour of operation. levelized marginal production cost for primary dispatchable units in the West Danish central electricity system suggests that for spot market prices below €33,3 per MWh, wind power is marginal as a result of being below levelized marginal production costs of any other dispatchable supplier. For spot market prices above this lower threshold, but below €44,7 per MWh, large-scale coal-fired power plants are marginal, and for prices of €44,7 per MWh or above, CCGT-plants are marginal. These thresholds reflect the current levelized marginal production cost of large-scale coal-fired power plants (€33,3 per MWh) and CCGT (€44,7 per MWh) when internalizing CO_2 emission costs and assuming long-term average efficiencies of 48 % for coal-fired power plants and 55 % for gas-fired power plants (Fig. 2). In result, CO_2 emission factors are 0,71 and 0,37 ton CO_2 per MWh net delivered electricity for coal and gas respectively. When wind power is marginal, marginal fossil energy consumption and marginal CO_2 emissions are assumed to be zero.

In reflection, this methodology is favourable to storage and relocation options that maximize net electricity production in periods where coal or gas are marginal, while minimizing electricity production and possibly maximizing electricity consumption in periods where wind is marginal.

After accounting for marginal CO_2 emissions in central electricity generation according to this approach, the CHP plant's resulting heat-related CO_2 emissions, including emissions related to the use of natural gas in the plant's supplementary heat-only boiler are subject to the aforementioned economic CO2 emission costs.

5. Results

5.1. Cold storage sizing

The size of the Cold Storage included with Option B, C, and D is found by simulating operation for various storage sizes maximizing operational economic income. Specific investment costs have been obtained and covers complete steel tank storages with 300 mm of insulation, instrumentation, nitrogen generator, and concrete foundation. Fig. 3 illustrates that the operational optimum is found to be between 200 and 300 m3, using 250 m3 for all options (equivalent to 10,4 MWh stored recovered heat).

In reflection, increasing the size of the Cold Storage will increase the share of heat production supplied by the heat pump unit and increase the relocation coefficient of the plant. However, for the comparative assessment of options B, C, and D, with A, E, and F, it is reasonable to settle for an economically feasible storage size.

5.2. Levelized marginal economic costs of operation of production units

Levelized marginal costs of operation for each production unit (CHP unit, HP/EB unit, boiler unit) are found and combined in operational strategy curves (Fig. 4), which are used to prioritize production units according to lowest marginal economic heat production costs under constraints of heating demand, electricity spot markets, production unit capacities, thermal storage and cold storage capacities, and production unit outages. The strategy curves internalizes CO2 emission costs and the shape of the curves, others than that of the boiler unit, in particular the shapes encountered for electricity spot market prices between €33,3 per MWh and €44,7 per MWh, is reflecting that the methodology on marginal CO2 emissions in central electricity generation applies these thresholds.

In reflection, identical operational strategies are used for all years in the planning period even though the cost of fuels and electricity varies from year to year. This problem is handled by using levelized marginal costs of operation that "averages" these variations.

5.3. Operational profiles and key operational plant-level results

Fig. 5, Fig. 6, and Fig. 7 illustrate operational profiles for selected options for a selected week of operation as found by operational optimization with respect to economic costs and benefits.

The illustrations show how the introduction of a heat pump allowing only for concurrent operation of CHP unit and HP unit (Option A compared to Reference) increases heating production capacity, which under constraint of the thermal storage reduces the number of full-load hours provided by the CHP unit, while furthermore reducing heat-only boiler operation. It is illustrated that the introduction of a Cold Storage to allow for independent HP unit operation (Option B compared to Option A) further reduces the number of full-load hours provided by the CHP unit, and further reduces heat-only boiler operation. The storage content profile for Option B's Cold

Storage shows the rates at which storage content increases while CHP unit operates, decreases while HP unit operates independently, and remains constant when CHP unit and HP unit operates concurrently.

Operational profiles are generated for all options for all weeks, and Table 1 summarizes aggregated operational plant-level results. It is found that the CHP-HP concept (Option A) increases plant-level fuel efficiency from 92,0% to 96,4%, and that adding a Cold Storage (Option B) further increases the efficiency to 97,2%, the highest efficiency for any option under analysis. This indicates that adding a HP unit to an existing CHP plant allowing for concurrent operation results in significantly higher plant-level efficiencies. When concurrent operation is disallowed for similar HP unit capacities (Option C and D), the efficiency increases from 92,0% to 93,5%. When concurrent operation is disallowed for HP/EB units with heating capacities similar to that of the CHP unit, the efficiency increases to 97,1% for the HP option (Option E) and not at all for the EB option (Option F), the latter clearly reflecting that for the calculation of plant-level fuel efficiencies an "exchange rate" of 1:1 for generated electricity and consumed electricity is assumed.

It is furthermore found that optimized economic operation of the CHP-HP concept allowing for concurrent operation only (Option A) results in the HP unit contributing 8,5% of total heat production and that adding a Cold Storage (Option B) further increases this share to 10,1%. When concurrent operation is disallowed for similar HP unit capacities (Option C and D), the share decreases to 3,2%. When concurrent operation is disallowed for HP unit heating capacities similar to that of the CHP unit, the share increases to 13,6% (Option E), the highest share for any option under analysis. The CHP-EB concept results in the EB unit contributing 2,4% of total heat production.

It is found that all options result in reducing the plant's net electricity delivery and in fewer full-load hours (relative to 3,48 MWe), lowest for Option E. Notably, the independent operation of the HP/EB unit (Option B-F) allows for the plant to consume electricity during periods when spot market prices for electricity are low and wind is marginal.

In conclusion, all relocation options increase the operational flexibility of the existing CHP plant resulting in lower gas consumption and higher plant-level fuel efficiencies for all HP options. However, all options reduce net electricity delivery from the plant, most notably for options allowing for concurrent operation of CHP unit and HP unit.

5.4. System-wide energy and environmental consequences

It is found that significant increases in plant-level fuel efficiencies may lead only to marginal increases in system-wide fuel efficiencies, and does not necessarily lead to reduced CO2 emissions. In particular this is the case for options that allows for concurrent operation of CHP unit and HP unit. The reason is that the reduction in net full-load hours and net electricity delivery is compensated by production at large-scale condensing plants, and that given constraints does not allow for any greater consumption of electricity in periods of low spot market price during which primary fossil energy consumption and CO2 emission are zero.

For CHP-HP (Option A) system-wide fossil energy consumption is reduced by 0,6%, however CO2 emissions increases by 22%. Similar for Option B, energy consumption is reduced by 2,3%, while CO2 emission increases by 21,7%. By disallowing concurrent operation of CHP unit and HP unit (Option C), primary fossil energy consumption is reduced by 0,5%, but CO2 emissions increases by 13,1%.

For Option D, not constrained by a limited heat source, the plant significantly reduces the gas boilers share of heat production to 3,9%, while reducing net electricity delivery only marginally, and further increases the share of electricity consumption in periods of low spot market prices. As a result, energy consumption is reduced by 5,1% and CO2 emissions are reduced by 9,2%.

The consequence of the HP unit's unconstrained access to a heat source combined with a much higher heat production capacity of the HP/EB unit than, is evident from results for Option E and F. For Option E, system-wide fossil energy consumption is reduced by 16,5%, while CO2 emissions are reduced 13,5%, the highest reductions for any option under analysis. For Option F, the lower conversion efficiency of an EB unit compared to an HP unit, results in lower reductions; 4,2% for fossil energy consumption and 8,5% for CO2 emission.

The results show that in order for HP/EB options to have positive system-wide energy and environmental impacts, independent operation of the HP/EB unit is required, concurrent operation of HP/EB unit and CHP unit should be discouraged, and for HP unit option heat source access should preferably be unconstrained.

5.5. System-wide relocation consequences

An option's relocation effectiveness in a particular energy system is reflected by the relocation coefficient *Rc*, defined as the statistical correlation between hourly net electricity delivery, and the energy system's electricity demand minus intermittent renewable energy production [8]. It is found that all options results in higher relocation coefficients thereby sustaining the hypothesis that the inclusion of HP/EB units with existing CHP plants may result in a significantly improved balance between distributed plant operation and electricity supply-demand fluctuations.

Rc increases from 0,518 for existing operation to 0,540 for Option A. The inclusion of a Cold Storage (Option B) further increases *Rc* to 0,547. Disallowing concurrent operation for similar HP heat capacities slightly reduces *Rc* improvements to 0,533 and 0,530 for Option C and D respectively. The highest relocation potential is found for Option E, reaching an *Rc* of 0,593 (Fig. 9).

5.6. System-wide techno-economic consequences and risks

Options are furthermore compared by levelized economic heat production costs and the cost-effectiveness of relocation. The cost-effectiveness of relocation is reflected by the *Rc*-shadow cost P_{Rc} defined as the economic net costs and benefits associated with increasing the relocation coefficient *Rc* by one %-point [8]. The evaluation of economic costs is subject to varying uncertainties that applies in particular to investment costs and CO2 quota costs. In an effort consistently to evaluate the sensitivity of economic results to these key uncertainties, a Monte Carlo risk analysis has been performed by which 200 scenarios for each option, totalling 1200 scenarios, have been analysed.

It is found (Fig. 10) that conclusions with respect to levelized economic heat production costs are only little sensitive to the suggested uncertainty ranges. Significantly higher economic production costs are found for Option E, while for other options economic costs amount to between €18 and €21 per MWh heat. For Option D samples are found that are below the median of the Reference option. Comparing medians it is found that Option A, B, C, D, and F result in 5-8% higher production costs than for existing CHP operation, while Option E results in 59% higher production costs.

It is found (Fig. 11) that conclusions with respect to P_{Rc} are very sensitive to the suggested ranges of uncertainty. For Option A, B and F, samples are found that are below the median of Option D. Comparing medians, it is found that Option D is the most cost-effective option for increasing the plant's relocation coefficient, followed by Option B.

In conclusion, while all options result in higher economic production costs compared to the Reference, Option D is likely to provide relocation most cost-effectively. However, Option A, B and F are potentially more cost-effective options with respect to relocation.

6. Conclusion

This paper presents a techno-economic modelling framework for evaluating options for increasing the effectiveness of CHP plants to match supply-demand fluctuations, characteristic to an energy system with high penetration levels of CHP and wind power, by addressing particular relocation options characterized by adding a large-scale heat pump with or without heat source storage, or an electric boiler to an existing CHP plant. The working hypothesis has been that relocation options may support further the penetration of intermittent energy resources and cogeneration, while increasing the robustness of distributed production units by reducing uncertainties related to fuel and electricity prices.

The modelling framework allows for options to be compared by relocation effectiveness, relocation cost-effectiveness, and system-wide energy and environmental impacts.

A system-wide economic cost assessment that internalizes CO2 emission costs is applied bottom-up from the level of optimized plant operational strategies under specified techno-economic constraints, and it is found that relocation benefits are likely to come at higher economic costs for options under analysis. However, as policy objectives are set to increase the energy system's flexibility, allowing for further penetration of wind power and distributed co-generation, and while various economic benefits from such policy are likely not to be reflected in the results, cost-effectiveness analyses are relevant.

It is found that unconstrained and independent operation of HP/EB unit is key to cost-effective relocation and that CHP-HP concepts (Option A, B, and D), despite higher investment costs and lower capacities, are likely to provide relocation more cost-effectively than CHP-EB concepts. Notably, it is found that a higher relocation coefficient is not necessarily identical to lower system-wide energy and environmental impacts in a particular energy system. Inherent to the applied modelling framework, detailed operational studies for specific options in specific energy systems are necessary to qualify options for providing both effective relocation, i.e. increases system flexibility, and reduced fossil fuel consumption and reduced environmental impacts.

It is found that the CHP-HP Cold Storage concept, i.e. the innovative idea of adding a Cold Storage for heat recovered from flue gasses that allows for the independent operation of a high-efficiency heat pump (Option B) leads to more cost-effective relocation than the CHP-HP concept not allowing for independent HP unit operation.

The results highlight a major challenge for relocation options leading to reductions in net electricity delivery from the CHP plant as this may possibly be jeopardizing system-wide fuel and environmental efficiency. It is shown that concurrent operation of CHP unit and HP/EB unit should be discouraged under the objective of increasing system-wide fuel and environmental efficiency.

All options considered, it is found that the most cost-effective, fuel and environmentally efficient option is likely to be Option D, i.e. CHP-HP Ground Source for which the capacity of the heat pump is similar to that of Options A-C. While Option D's COP is considerably lower than for options that utilizes cooling and condensing of flue gasses (Option A, B, C), lower investment costs and unconstrained operation of the heat pump allows for this option to outperform other options under analysis here. However, land use costs are not considered, which is potentially of critical relevance to Option D. Also major uncertainty exists as to whether a transcritical CO2 heat pump will allow for the required high exit temperatures on the basis of ground source temperature levels, required for independent HP unit operation, thereby questioning the technical viability of Option D. At present, practical experiments with CO2 heat pumps are mainly based on relatively high temperature levels of the heat source. For low-temperature heat sources pressure differences may simply be too high to handle.

These concerns have guided the focus of a new research project granted in December 2006 by Energinet.dk, the Danish TSO, awarding Aalborg University, EMD International A/S, Danish Technological Institute, and Advansor A/S €1,5 mill. for a full-scale CHP-HP Cold Storage demonstration project that will explore further the feasibility of relocation focusing on developing further the concept analysed here as Option B and C.

6.1. Effective policy instruments

The Danish government has introduced instruments to stimulate relocation and the move towards a 2nd generation renewable energy system. However, these instruments are aimed at stimulating the introduction of electric boilers (Option F).

In December 2005, the Danish Folketing agreed on Law L1417 [28] that introduces incentives to promote the relocation-driven use of electricity. L1417 introduces changes to existing energy and environmental taxes, most notably with respect to the taxation of the use of electricity for district heating production. Prior to L1417 any use of electricity for heating production, also self-produced electricity, was subject to an energy and environmental tax of DKK 0,665 per kWh.[†] With L1417 this tax is reduced to DKK 50 per produced GJ of district heating[‡] for non-concurrent operation of CHP and EB/HP unit.

While the non-concurrency issue from a narrow perspective is appreciated by policy makers, the problem with L1417 is that while promoting relocation-driven use of electricity, it penalizes the efficient use of electricity. As the new energy and environmental tax is calculated on the basis of district heating production, not on electricity use, the more efficient use of electricity, the higher the resulting tax per kWh of consumed electricity. While the tax for electricity used in an electric boiler is reduced by 73% (from DKK 0,665 per kWh to DKK 0,18 per kWh), the tax for electricity used

[†] DKK 0,576 per kWh (energy tax) plus DKK 0,09 per kWh (CO2 tax). €1 equals DKK7,45

[‡] DKK 45 per GJ (energy tax) plus DKK 5 per GJ (CO2 tax).

in an efficient compression heat pump is reduced only by 5% (from DKK 0,665 per kWh to DKK 0,63 per kWh)[§].

What alternative policy instruments would be better at stimulating cost-effective relocation options?

A key practical problem is that Option A is already financially attractive for many applications, but current energy and environmental taxation policies requires for any CHP-HP application to select mechanically driven compression heat pumps in order to avoid electricity use taxation, thereby allowing only for concurrent operation of CHP-unit and heat pump. This results in plant-level fuel savings and fuel efficient plant operation, but it does not allow for relocation-driven use of electricity. Under current policies, electric-drive compression heat pumps, and thereby relocation by means of heat pumps, is strongly discouraged.

In response, Aalborg University and The Danish Society of Engineers is recommending for the Danish Folketing to allow for the compensation of energy and environmental tax of up to 10% of self-produced electricity for use in compression heat pumps producing district heating [29]. This would immediately have plant operators considering Option A choose an electric-drive rather than a mechanically driven heat pump, allowing for relocation-driven use of electricity, if combined with a Cold Storage (Option B).

But would the proposed “10%-instrument” not stimulate concurrent operation of CHP unit and HP unit, thereby possibly resulting in increasing system-wide CO2 emission as documented by this paper? Yes, it is likely to in a narrow perspective, however, the instrument should be evaluated with respect to the perspective by which Denmark is obligated to CO2 reductions; The “10%-instrument” would result in increasing CO2 emissions from condensing plants, but this would lead to obligatory efforts for introducing more wind power and CHP thereby altering the marginal system-wide assumptions applied in this paper and fulfilling the core objective of introducing relocation. In other words, the “10%-instrument” would indirectly stimulate further the penetration of CHP and wind power, thereby bringing the energy system towards a state in which CHP-HP/EB plants becomes marginal producers/consumers.

Constraining the instrument to 10% of self-produced electricity would secure that existing CHP plants are not completely replaced by full capacity heat pumps, sustaining the principle of co-generation.

In reflection, it is relevant to add that large-scale heat pumps should not be regarded an efficient alternative to electric boilers, but rather as an integrated system component that may contribute to increased operational flexibility. Our reviews of heat pumps in district heating production shows that applications are highly localized, utilizing whatever low-temperature heat source is available, ground or rock-source, solar, sea, lake, waste water, ambient air, cooling demand. The specific availability and temperature level of this localized low-temperature heat source results in a large range of different designs, COPs, and operational strategies.

With CHP-HP Cold Storage (Option B), we are introducing a general application and standard for the integration of heat pumps with existing CHP plants that utilizes heat recovered from flue gasses or intercooling, resulting in a much predictable and fully integrated relocation option, that is also efficient and cost-effective.

[§] For a COP of 3,7.

6.2. Technical potential for cost-effective relocation

If successful, a 1st generation CHP-HP Cold Storage concept should be penetrating markets during 2007-2012. The technical potential in Denmark is about 200 MWe (heat pump electrical-drive power rating). However, the project should be seen only as the first step towards the 2nd generation CHP-HP Cold Storage concept that introduces supplementary low-temperature heat sources, like ground-source. To a certain extent, this may be an to some CHP production in the long-term future, thereby representing a technical potential in Denmark of about 900 MWe (heat pump electrical-drive power rating). Initial targets could be to set to achieve market penetration for 2nd generation concepts during 2010-2015.

Acknowledgements

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Figure captions

Table captions

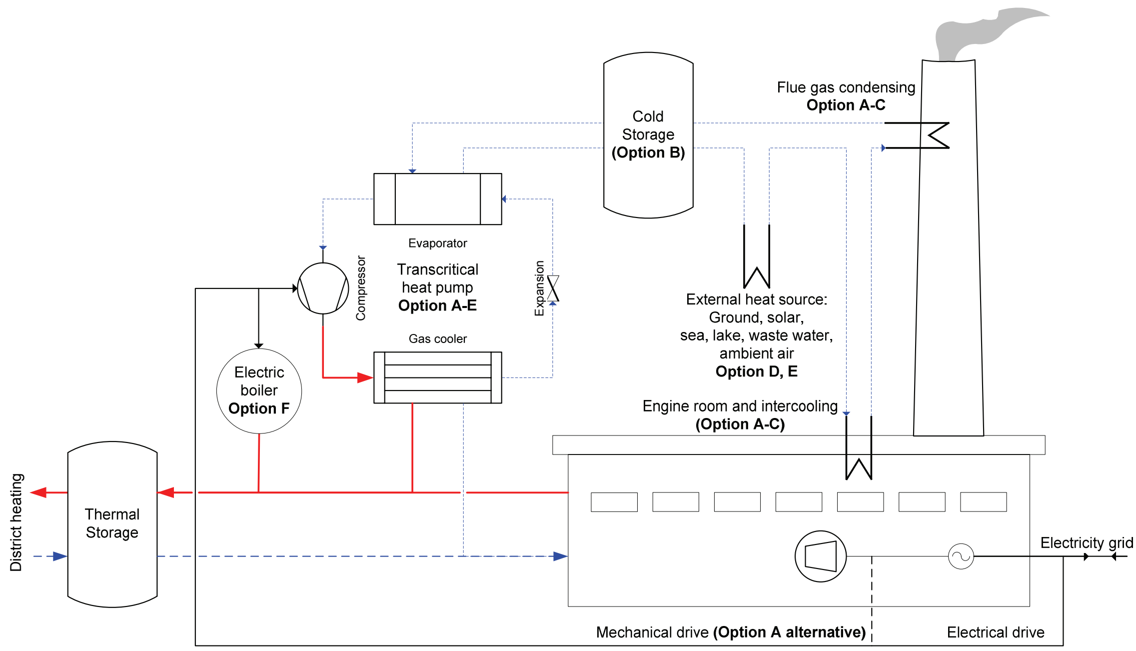

Fig. 1: Combined illustration of CHP-HP/EB concepts under analysis.

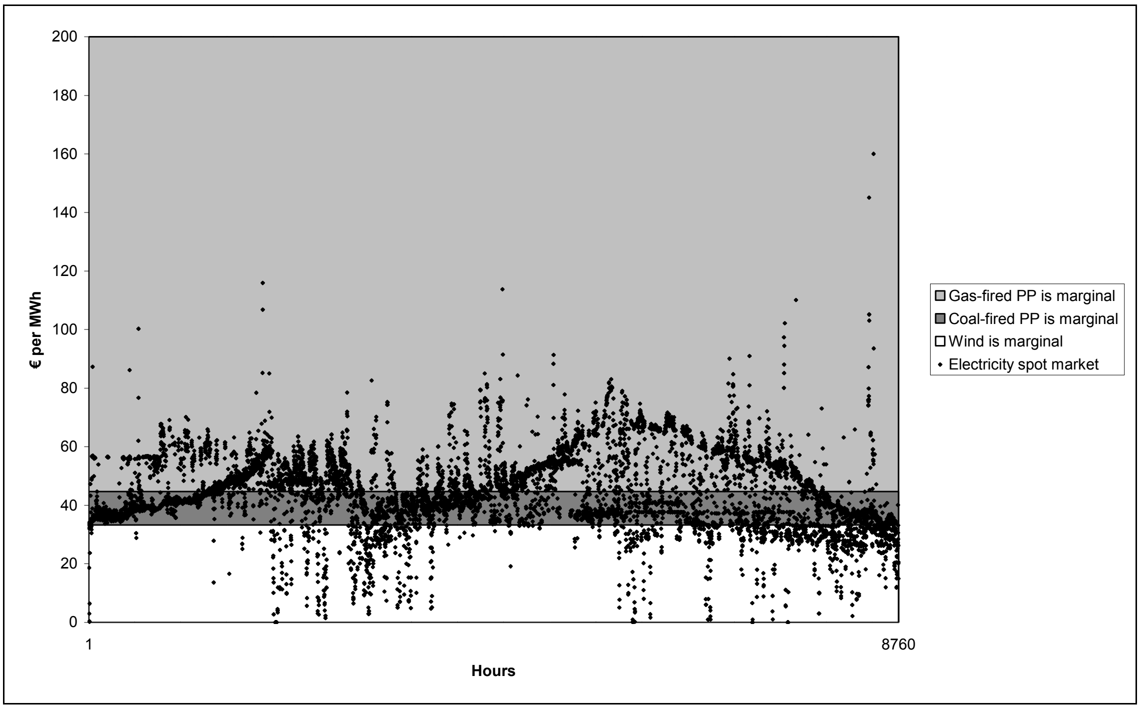

Fig. 2: Marginal production in central electricity generation as a function of 2006 spot market price fluctuations.

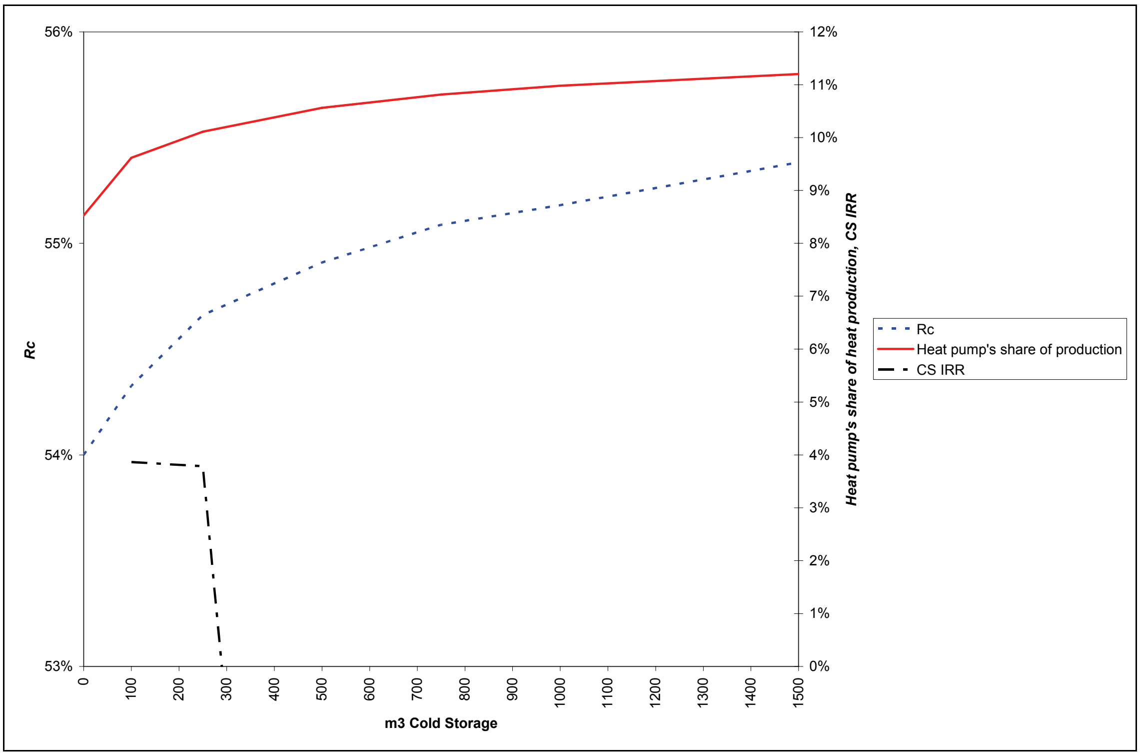

Fig. 3: Relocation coefficient *Rc*, HP unit's share of heat production, and economic IRR on Cold Storage investment by Cold Storage size.

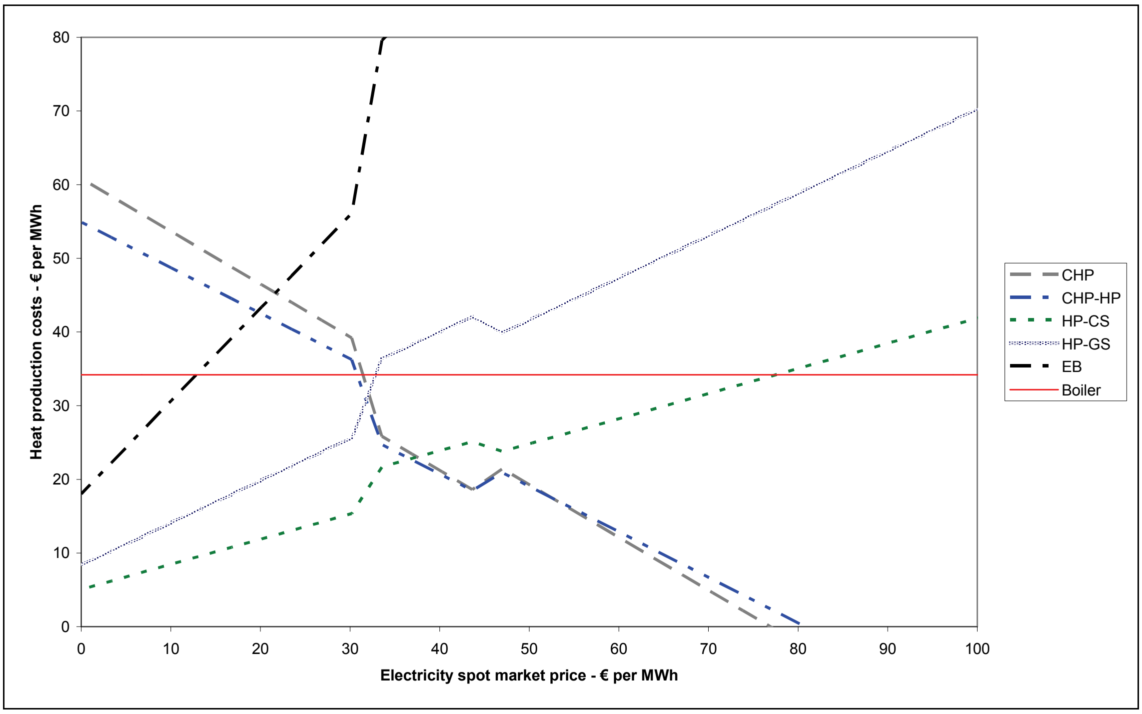

Fig. 4: Levelized marginal costs of operation per kWh heat delivered.

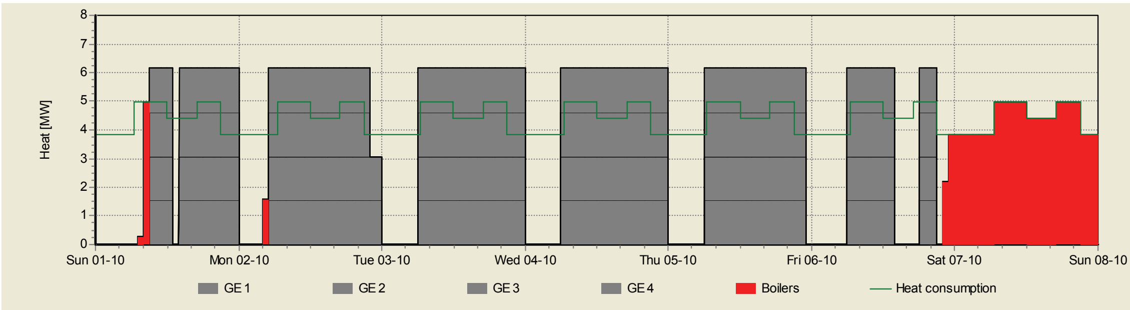

Fig. 5: Reference: Heat production by production unit for the first week of October 2006 (Week 40).

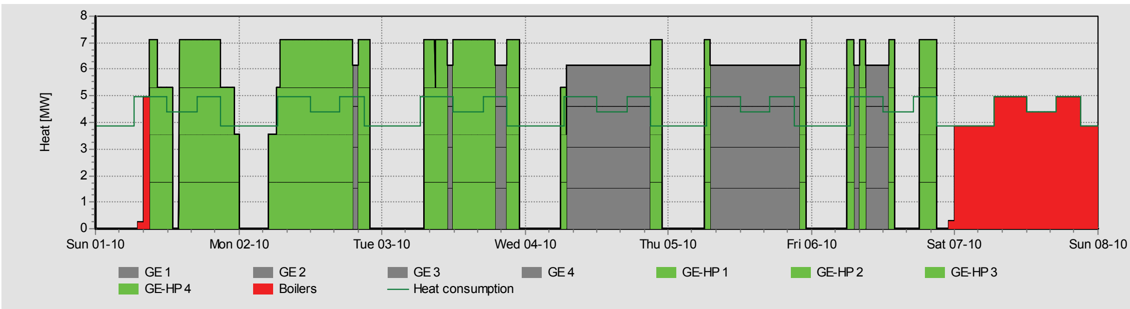

Fig. 6: Option A: Heat production by production unit for the first week of October 2006 (Week 40).

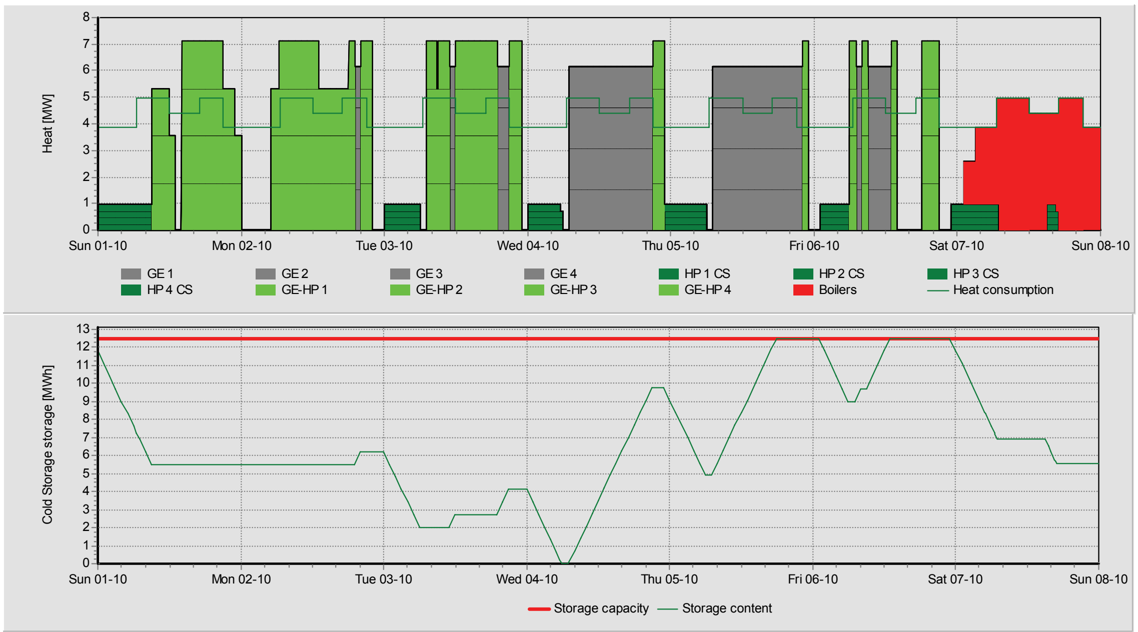

Fig. 7: Option B: Top: Heat production by production unit. Bottom: Cold Storage content profile. For the first week of October 2006 (Week 40).

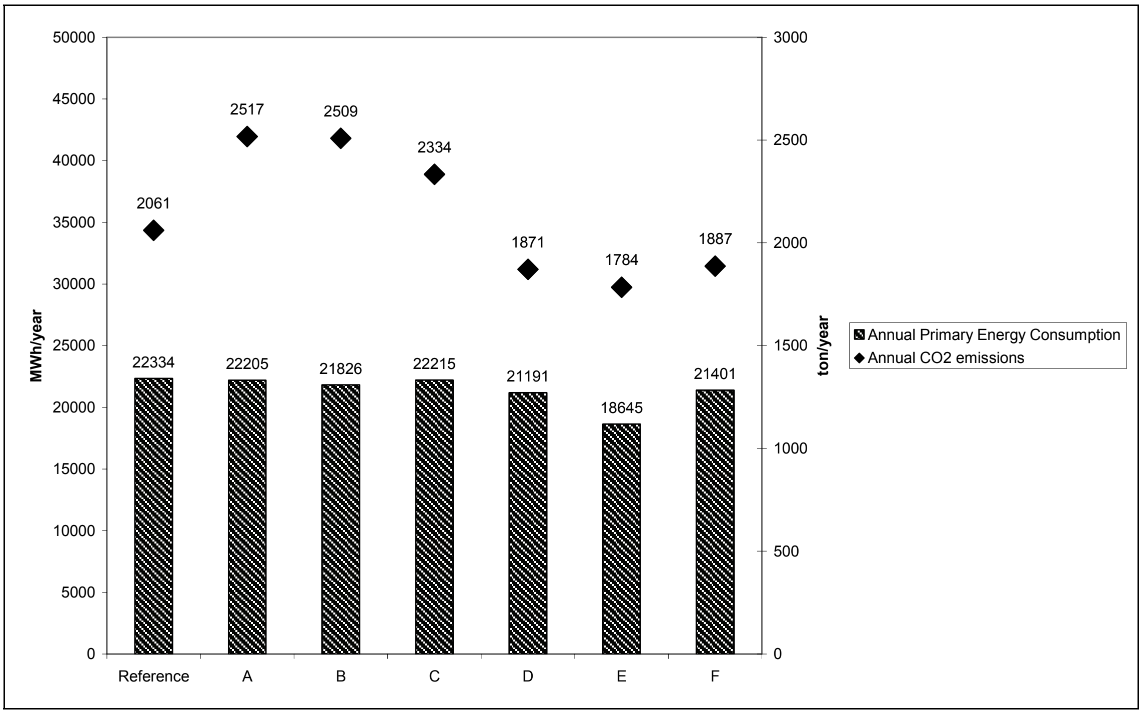

Fig. 8: System-wide energy and environmental consequences.

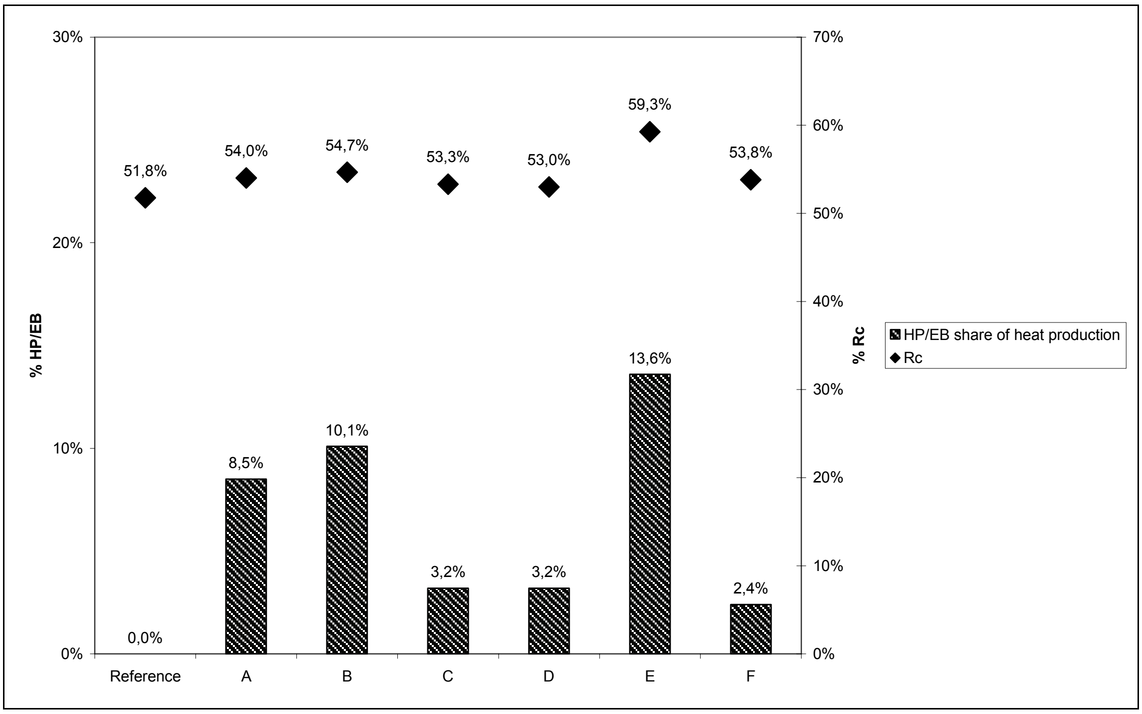

Fig. 9: Correlation between plant's electricity balance and the system's electricity demand minus wind production (*Rc*) and HP/EB unit's share of heat production by option.

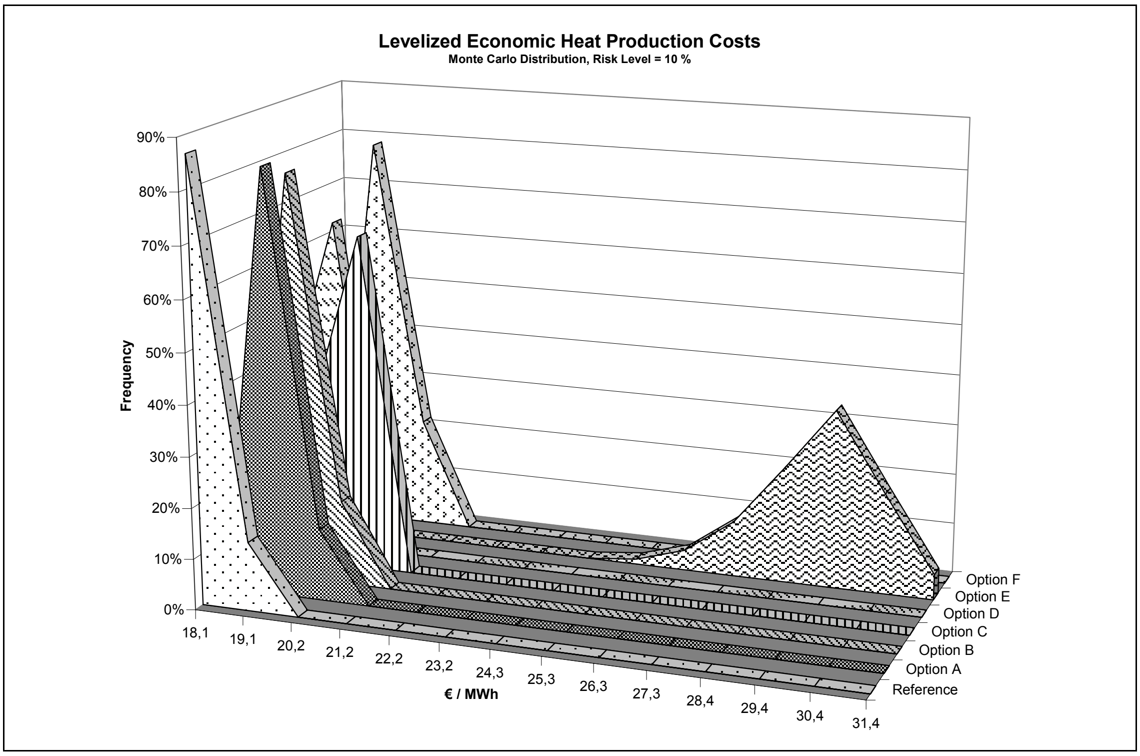

Fig. 10: Monte Carlo ranges for levelized economic heat production costs.

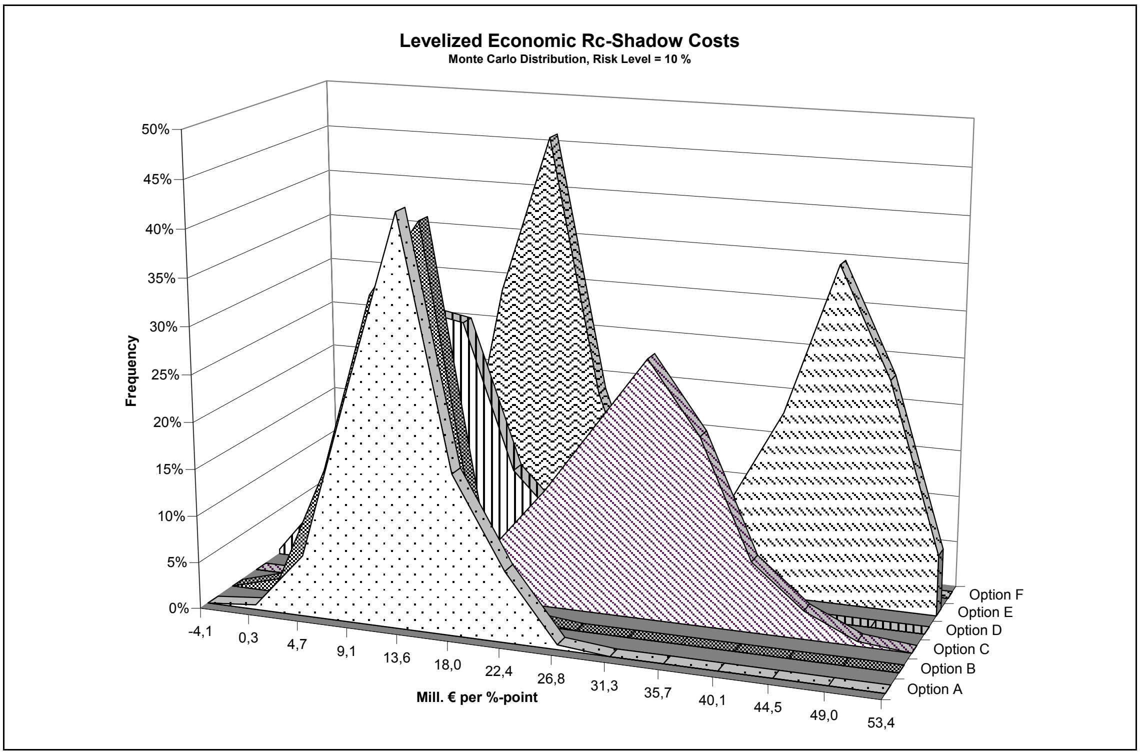

Fig. 11: Monte Carlo ranges for levelized economic *Rc*-shadow costs.

Table 1: Key operational plant-level results

Option	Unit	Reference	A	B	C	D	E	F
Description		CHP	CHP-HP	CHP-HP-CS	CHP-HP-CS	CHP-HP-GS	CHP-HP-GS Full	CHP-EB Full
Concurrency		Allowed ->			Disallowed ->			
CHP-HP/EB fuel efficiency	%	92,0%	96,3%	97,2%	93,5%	93,5%	97,1%	92,0%
HP/EB share of heat prod.	%	-	8,5%	10,1%	3,2%	3,2%	13,6%	2,4%
Boiler share of heat prod.	%	6,5%	4,9%	4,4%	7,4%	3,9%	0,0%	4,4%
Plant gas consumption	Mill. m3/year	5,84	5,36	5,28	5,63	5,70	5,17	5,74
Net electricity delivery	MWh/year	20.454	18.045	17.654	19.227	19.989	16.495	19.450
Net full-load hours	Hours/year	5.877	5.185	5.073	5.525	5.744	4.740	5.589
- high/gas	%	59,6%	63,0%	64,2%	63,3%	60,9%	73,2%	62,6%
- int/coal	%	40,4%	37,0%	36,6%	37,9%	40,6%	40,6%	42,2%
- low/wind	%			-0,7%	-1,2%	-1,6%	-13,8%	-4,8%

Table 2: Risk ranges levels used for Monte Carlo risk analysis and median key results.

Parameter	Unit	Reference	A	B	C	D	E	F
Uncertainty range CO2 quotas	*± %*	*50%*						
Uncertainty range investments	*± %*	-	*20%*	*30%*	*30%*	*20%*	*30%*	*10%*
Median levelized economic heat production costs	€ / MWh	18,3	19,2	19,4	19,8	18,7	29,1	19,4
Median P_{Rc}	Mill. € per %-point	-	13,3	11,4	30,8	11,1	44,4	17,4

Energy system analysis of large-scale heat pumps

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Abstract

Contemporary energy policy and planning rests on advanced system models for comparing energy options. But few system models are well prepared for assessing the comparative techno-economic feasibility of relocation and storage options in renewable energy systems. This paper describes the principle of relocation in renewable energy systems, and explores how large-scale heat pumps in combination with distributed combined heat and power plants may be evaluated by energy system analysis. As a basis for developing realistic scenarios for the Danish energy system, the paper combines different bottom-up energy system models in assessing the impact of introducing large-scale heat pumps with respect to the interaction between energy, economy, and environment, allowing for the subsequent evaluation of energy system analysis methodologies with respect to comparing power exchange, storage, and relocation options in systems that support high penetration levels of wind power and CHP.

Keywords: Bottom-up energy system analysis; storage and relocation; large-scale compression heat pumps; CHP-HP Cold Storage.

Nomenclature

3E	Interaction between energy, economy, and environment
CHP	Combined heat and power
CHP-HP	CHP plant with heat pump
CHP-HP-CS	CHP plant with heat pump and Cold Storage
COP	Coefficient of performance
CS	Cold Storage
DKK	Danish kroner (100 DKK = €13,42 = USD18,31)
EB	Electric boiler unit
HP	Heat pump unit
LC	Least costs
MP	Market power
TSO	Transmission System Operator
TWh-q	MWh heating capacity

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1. Introduction

The future of intermittent energy resources rests on successfully increasing energy system flexibility [1,2]. System flexibility may be increased by introducing storage and relocation options such as electrical energy storage facilities [3], pumped hydro storage [4], hydrogen production and storage [5], compressed air energy storage and biomass gasification [6], vehicle-to-grid systems [7], or as in focus of this paper, by integrating large-scale compression heat pumps with combined heat and power plants [1,8]. But how are such options best evaluated in energy system analysis with respect to the interaction between energy, economy, and environment?

There are two basic methodological approaches for modelling the interactions between energy, economy and environment: top-down and bottom-up. The top-down approach typically describes the energy system in an aggregated way and as a sub-sector of the entire economy, and the results are mainly induced by relative price changes. The bottom-up approach considers the energy sector in techno-economic detail, and the results are mainly engineered by user-specified technological changes.

While these two approaches are complementary rather than competing, they are often seen representing opposing professional and ideological positions in energy systems analysis. Efforts have been made for developing hybrid models, combining techniques and principles from these two approaches, and future model developments are certain to benefit from such efforts [9,10,11,12].

Compared to top-down modelling, a key issue in bottom-up modelling is that it does not include a complete model of economic activity, for example bottom-up models do not allow for evaluating economy-wide lost opportunity costs from increasing investments in particular technology areas. Another key issue is the use of exogenous assumptions for future techno-economic characteristics [13].

Our research is dealing with the suggested need for, and consequences of specific technological innovations, and in our efforts evaluating these consequences, we have found that this ability is available by using bottom-up models. This is not saying that top-down models are not able, nor that bottom-up models evaluates consequences particularly well, in fact, the key purpose of this paper is to evaluate current approaches in bottom-up modelling, while discussing requirement specifications for improving the state of energy systems analysis. We do so by comparing methodologies and results from three bottom-up energy system models recently applied for policy analyses in Denmark, when evaluating the consequences of introducing large-scale compression heat pumps as a means for increasing system flexibility by relocation.

2. Large-scale compression heat pumps for relocation

A relocation technology introduces flexibility by bridging energy carriers and represents an innovation in renewable energy system design [14]. An electric boiler (EB) provides simple relocation of electricity to heat. A compression heat pump (HP) provides efficient relocation of electricity to heat and/or cooling [15].

Large-scale compression HP units may be introduced into the energy system in various configurations, reflecting demand and heat source characteristics. Applications are found for both industrial and commercial heating and cooling purposes. In our research, we are focusing on the application of large-scale compression HP units for district heating purposes for which two basic types are currently being considered: stand-alone HP units using external heat source resources such as ground source, solar heat, sea, lake, waste water, or ambient air; and integrated HP units using internal heat resources, mainly flue gasses available from the HP unit's being integrated with CHP unit and/or boiler units.

Fig. 1 illustrates basic HP and EB options for integration with a CHP plant.

On the basis of detailed case-studies, we have earlier investigated the feasibility of HP units being integrated with CHP plants and found that in the current energy system characterized by condensing coal-fired and gas-fired power plants dominating as marginal production units, concurrent operation of CHP unit and HP unit should be disallowed as reductions in net electricity delivery from the CHP plant jeopardizes system-wide fuel and environmental efficiency [1,8,16]. But even with concurrent operation disallowed, the integration of HP or EB units will, under given constraints mainly from heat demands and thermal storages, reduce CHP unit operation, reducing net electricity production, which may jeopardize the potential system-wide benefits from introducing relocation technologies in combination with CHP plants.

A most promising and possibly feasible option is the CHP-HP Cold Storage concept that adds an electrical compression heat pump and a thermal storage (Cold Storage) to a CHP plant. The Cold Storage stores low-temperature heat recovered from low-pressure cooling and condensation of flue gasses whenever the CHP unit is in operation. When the HP unit operates, it generates cold water which is stored for subsequent low-pressure cooling and condensing of flue gasses, in the case study from 60°C to 30°C. The Cold Storage handles these temperature levels ranging from 20°C in the bottom of the storage tank to 60°C in the top. Possibly the Cold Storage is better an integrated part of the thermal storage, then ranging from 20°C bottom of the storage tank to 90°C in the top. In any case, the recovered heat is stored and operated as an integrated heat source, allowing for high-efficiency operation of the heat pump without concurrent operation of the CHP unit. The CHP unit and the heat pump may in principle also be operated concurrently utilizing heat recovered from flue gasses directly, in principle by-passing the Cold Storage.

But how is this option described in bottom-up energy systems models claiming to hold a complete representation of the interaction between energy, economy and environment? What are major limitations, and how may bottom-up models better approach energy system innovations implied by principles of storage and relocation?

3. Models authenticity evaluation

We have explored and compared methodologies, assumptions and results from three models applied in energy systems analysis during 2005-2007 claiming to provide an energy system analysis evaluating 3E interactions for 2010: EnergyPLAN, SIVAEL, and RAMSES. Several other system models have been applied in the context of Danish national energy planning during this period; including Nordic market power models MARS, Samkøringsmodellen, and bottom-up models Balmorel, Energistrømsmodellen, SESAM. These models are all very different in terms of ownership and context, and are primarily aligned in claims for attending to a system-wide scope and in efforts competing for the attention of policy makers.

For the purpose of this paper, system analysis has been confined to elements of demand and supply of electricity and district heating. While some models may provide such abilities within their scope, all analyses here excludes transportation demand, and individually supplied heating demand, other than included under electricity demand.

The EnergyPLAN model [17] is developed by Aalborg University for Danish energy systems analysis as well as for educational purposes. Working on a high level of aggregation with respect to plants and grids, the model analyzes the consequences of hourly variations in demand and supply for one year of operation. On the demand side, the model allows for the user to specify a global electricity demand and an associated hourly profile, a few categories of individual and district heating demands, a few categories of individual and district heat-driven cooling demands, both with associated hourly profiles, as well as aggregate fuel demands for industry and transportation. On the conversion side, the user is able to specify three groups of CHP plants and boiler plants, one group of condensing plants. On the resource side, the model allows for the user to specify four intermittent renewable electricity producers with associated hourly profiles, a few solar heating producers, and a single breakdown of all fuel use by associated groups of district heating boilers, CHP and condensing power plants. On the side of exchange, storage and relocation, the user may specify fixed electricity import/exports, a single electricity export transmission line capacity, and two categories of heat pumps in district heating. For situations of any non-exportable excess power production, the model has routines for cost-effectively handling storing or relocating. The model attempts to handle specific storage and relation options, such as vehicle-to-grid, electrolysers, compression heat pumps, and compressed air storage.

The SIVAEL model [18,19] is developed by energinet.dk, the Danish TSO and is being used for various short and long term planning task. In the data set used here, SIVAEL simulates and optimizes according to least operational costs the dispatching of all major units in the Danish power system, aggregating minor distributed plants by location and fuel. Actual dispatching of plants is controlled by the user by specifying shadow prices for various producer data. Each plant is described in detail with up to three fuels. The hourly simulation includes constraints and costs associated with starting and stopping of units. SIVAEL hold advanced stochastic wind production routines, and may for example be used to simulate the need for balancing services due to inaccurate wind production prognoses. On the side of exchange, storage and relocation, SIVAEL handles electricity market exports and imports under deterministic price and transmission constraints. The user may specific localized electric batteries, pumped storage, electric boilers or heat pumps.

The RAMSES model [20] is developed by the Danish Energy Authority and is being used for major national energy and environmental planning purposes, and also for UNFCCC inventories and the Danish Energy Authority's evaluation of public and private projects. RAMSES holds very detailed datasets about current and planned individual plants and distribution grids, electricity and district heating plants, the transmission system, fuel cost projections, taxation, and emission quota. While RAMSES is not available for our model runs, it is included here under Reference scenarios as both EnergyPLAN and SIVAEL applies assumptions provided as outputs from some of RAMSES' scenarios.

While all models are practically localized to the Danish energy system, both EnergyPLAN and SIVAEL are in principle open for application for a user specified energy system. Both EnergyPLAN and RAMSES are characterized by a very wide system scope, attempting to incorporate all sectors and market. RAMSES and SIVAEL are characterized by offering a very detailed breakdown of demand and supply into end-users, particular grid, and single plants. EnergyPLAN is characterized by offering a highly aggregate model for capturing the same system. RAMSES is characterized by iteratively applying top-down models for macro-economic consistency. The level of aggregation is apparent in the micro-economic decision model leading to system simulations, which, for all models, are based on the principle of least marginal costs of operation, both EnergyPLAN and RAMSES considering the impacts of bottleneck on electricity prices, RAMSES furthermore considering the impact of producers exercising market power on electricity prices. All models are similar with respect to having a very limited user and developer base.

While the three models are characterized by their context and are providing advanced energy system analyses in their own right, Table 1 attempts to provide a comparative evaluation of characteristics and authenticity of EnergyPLAN, SIVAEL, and RAMSES with respect to Danish energy system analysis.

4. Reference scenarios for 2010

It is reasonable to distinguish between assumptions and results, however due to the varying nature of the models and their internal praxis of interacting with other models, Table 2 holds a number of key assumptions, some of which may also be labelled intermediate results. For example, the electricity demand in RAMSES is a result of detailed modelling of end-users under new energy conservation regulations and also consistent with Government macroeconomic projections, as such it enters RAMSES as an iterative assumption, but it is also a result out of RAMSES' context. In fact, this result is used as an assumption directly in EnergyPLAN. For SIVAEL, production figures for boilers, CHP units, and condensing power plants are results of an operational least cost optimization for the Reference Scenario, while for EnergyPLAN, these results are applied as assumptions.

All models evaluate the energy system based on an hourly representation of data, SIVAEL also allows for data to change for each production unit hour by hour. Of particular interest with respect to hourly fluctuations and the role of exchange, storage and relocation, Fig. 2 illustrate the hourly demand for electricity, district heating, and intermittent electricity supply from on-shore and off-shore wind power as applied in EnergyPLAN, SIVAEL, and RAMSES respectively. In fact, SIVAEL includes advanced models for analysing stochastic variations in wind production, and all models may use any hourly profile; the data illustrated here reflects the latest data used for published works for 2010.

Legends are excluded in Fig. 2 as the charts barely allows for distinguishing between legends anyway, however the illustrations provide a telling view of key balancing challenges dealt with in advanced energy system analysis.

It is noted that while fluctuations in electricity demand are very similar, supposedly due to an extensive amount of historic data, district heating demand fluctuations shows significant differences, supposedly due to all models' habit of applying one historic data set from one of the large district heating networks assumed similar for all grids (if more than one). For on-shore wind production load curves are similar, while for off-shore wind production different datasets are obviously applied, resulting in different load curves being assumed.

Numerous techno-economic assumptions apply, for example fixed and variable operational costs, but are left for default values according to the models' last use for published works on the Danish energy system. Of particular importance, both EnergyPLAN and SIVAEL apply a CO2 shadow costs of DKK 150 per ton on production units, and EnergyPLAN assumes a single transmission line capacity of 2500 MW.

Having prepared a Reference Scenario for 2010 in EnergyPLAN and SIVAEL, while relying on a breakdown of the latest projections for 2010 based on RAMSES analyses presented in June 2005 by the Danish Energy Authority [21] reflecting impacts from the agreed energy conservation policy currently under implementation, Table 2 combines key Reference Scenario results.

Net electricity export in 2010 is found to be in the range of 28-39 % of domestic electricity demand. High electricity export levels are due to higher price levels in neighbouring grids in Nord Pool, but may also be seen as a result of lower domestic market prices due to high penetration levels for wind power and CHP. Not subtracting income from electricity exports, total operational costs are found to be just less than DKK 13 billion per year according to EnergyPLAN and SIVAEL.

Primary fuel consumption in 2010 excl. renewables other than biomass is found to be in the range of 93-124 TWh; most notably the share of coal is higher in SIVAEL. CO2 emissions are found to be in the range of 21-33 million ton per year.

In reflection, these results cannot be appreciated without reference to the corresponding assumptions as well as to the model context. However, it is interesting to observe the significant differences in-between the reference scenarios even for a system modelled on a 3 year horizon, and even when attempting to harmonize techno-economic assumptions.

5. Partial heat pump scenarios for 2010

Keeping identified differences and incompatibilities in mind, what are the consequences according to system analysis models EnergyPLAN and SIVAEL of having introducing a 100 MW-q compression heat pump for district heating in the Danish energy system in 2010, all other things equal? RAMSES is a proprietary tool and was not available for this exercise.

As suggested by Blarke in [8], two basic types of large-scale heat pumps seems relevant for consideration in the short to medium term: stand-alone HP units using external heat source resources such as ground source, solar heat, sea, lake, waste water, or ambient air, and integrated HP units using internal heat resources, mainly flue gasses, available from the HP unit’s integration with CHP plants or boilers, possible introducing a Cold Storage allowing for inconcurrent operation of HP unit and CHP unit. The resulting COP and operational economics of a heat pump scenario is dependent upon the choice of concept or combination of concepts.

Both EnergyPLAN and SIVAEL allows directly for analysing stand-alone HP units or electric boilers supplementing existing CHP unit and boiler operation. Assuming a COP of 3,5, reflecting an optimistic ground source COP, and a shadow cost of DKK 0,567 per kWh electricity consumed by the HP, reflecting the existing energy and environmental taxation level for using electricity for district heating production, alternative scenarios were developed for both models.

Neither EnergyPLAN nor SIVAEL allows directly for analyzing the CHP-HP-CS concept, i.e. the integration of a heat pump and a Cold Storage with a CHP plant, allowing for independent operation of the HP unit using flue gasses for heat source. In this concept, the HP unit operates under constraint of a Cold Storage and such a constraint may neither be specified in any of the models.

With EnergyPLAN, the HP units are included with the aggregate group of central CHP plants in the aggregate group of the central district heating grid. With SIVAEL, the HP unit is placed as a stand-alone heat pump supplying Aarhus District heating grid.

It is found that despite having different reference scenarios, SIVAEL and EnergyPLAN provide almost identical results with respect to consequences relative to the reference scenarios. Fig. 3 shows that primary fuel consumption, CO2 emissions, net electricity exports, and operational costs, excluding any value of carbon credits as well as the depreciation of investments, are all lower in the alternative scenario; primary fuel consumption is reduced by between 0,2 % and 0,3 %, net electricity exports is reduced by around 1,2 %. operational economic costs is reduced by 0,3 %, while domestic CO2 emission reductions amount to 40,000 ton per year in both analyses, corresponding 1,400 ton per year for each MWe HP unit..

The calculated reduction in CO2 emissions is likely not obtained in praxis as the supply of electricity and district heating is subject to carbon quotas. However, the reduction carries an economic benefit in terms of freed carbon credits. Considering investment costs of €2,0 mill. per MWe[†] for the HP unit plus €0,4 mill. for ground source heat uptake[‡], an economic discount rate of 6 %, and an assumed life time of 20 years at given O&M costs, the economic costs of freed carbon credits amount to €214 per ton according to EnergyPLAN and €242 per ton according to SIVAEL.[§] This is significantly higher than projected carbon credits at €23 per ton readily supports.

The result supports the understanding that the introduction of unconstrained large-scale heat pumps in district heating results in a more resource-efficient energy system, better domestic integration of intermittent supply (reduced exports), and non-cost-effective CO2 emission reductions. However, EnergyPLAN and SIVAEL does not readily allow for the evaluation of more advanced concepts for relocation, including the CHP-HP-CS concept. Furthermore, neither model considers the potential benefits that relocation technologies may provide in terms of possibly avoided infrastructure costs.

With respect to the methodological perspective of this article, it is found that system models EnergyPLAN and SIVAEL provides a consistent evaluation of the consequences of introducing large-scale compression heat pumps into the Danish energy system by 2010, even on the basis of quite different resulting reference scenarios for 2010.

6. Conclusion

Earlier efforts have been applying a bottom-up case study perspective using a simplified marginal approach for energy system consequences [8,23] for assessing the comparative technical and economic effectiveness of introducing large-scale heat pumps into an energy system with high penetration levels of intermittent renewables and CHP. This paper is taking stepd for these advanced CHP concepts, and other

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[†] Excluding CS and chimney core in stainless steel, i.e. 76% of the investment costs for the CHP-HP-CS concept. [22]

[‡] Estimated at €0,16 mill. per MWq excluding costs of land [22].

[§] Economic factor prices, excluding fiscal costs and costs of carbon credits.

exchange, storage and relocation options, towards the level of energy system analysis, exploring state-of-the-art routines for handling 3E interactions.

It seems however relevant to suggest for both EnergyPLAN and SIVAEL to undergo further developments in preparation for evaluating advanced CHP concepts such as the CHP-HP and CHP-HP-CS concept, for example with respect to concurrent or inconcurrent operation of production units, constrained low-temperature heat sources, and the use of cold and thermal storages. This involves combining energy system models and operational energy project analysis models, for better incorporating the micro-economic basis upon which individual production units at the plant is dispatched under given constraints.

With respect to the need in planning for system models that analyzes large-scale penetration of particular technology options into the energy system, it seems relevant to suggest for models like EnergyPLAN and SIVAEL to improve in terms of user-friendliness and accessibility. In an age where software is becoming a primary platform for interacting on important techno-economic planning problems, why is it so difficult to find resources for bringing energy system analysis into an era of interactive energy planning? Google would certainly afford an idea of similar relevance to them, but hope is faint for seeing such serious public or private investments in something this so neither funny nor sexy [24].

In reflection, any application of 3rd party energy system models should take a number of issues into account, including:

1. The architecture and methodology of the energy system model is highly influenced by the context from which it has been developed. The rationality that it depicts is explained by this context.
2. Very few energy system models are available cross-professionally and cross-culturally. A good example of one system model that provides such accessibility is LEAP, which should be considered as an alternative to proprietary and local energy system models.
3. Risk is a key analytical parameter in planning, and planning software should do better to establish such understanding at point of entry, for example by allowing for extensive risk analyses. A good example of one energy project model that allows for risk analyses is RetScreen.
4. The evaluation of distributional costs and benefits are not readily supported in energy system models, making it difficult for the planner to assess “winners” and “losers”. Bottom-up models need to do better in terms of evaluating the distribution of economic costs and benefit by economic interest, including the evaluation of fiscal costs, financial costs, balance of payment costs, and employment impacts.
5. Market price simulations, price-demand feedbacks, and game theory is new turf in bottom-up energy system analysis. The RAMSES model includes such components, but is a proprietary and inaccessible software tool.

Acknowledgements

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Figure captions

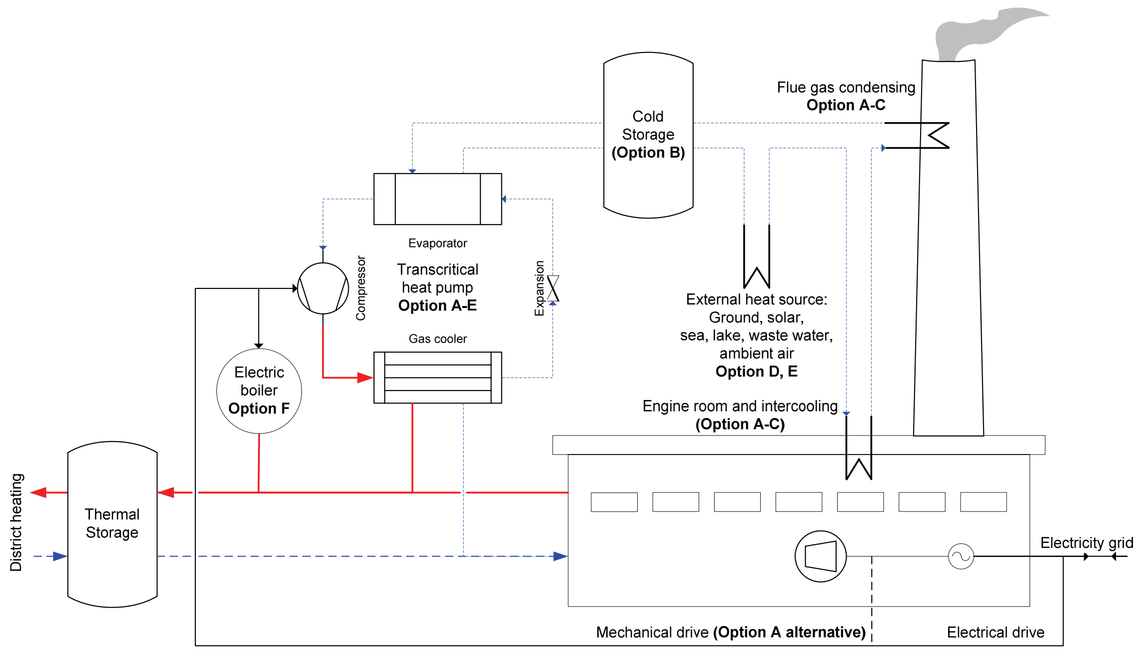
Fig. 1: Illustration of the CHP-HP-CS concept under analysis. Options refer to options analyzed in [15]. CHP-HP is Option B and CHP-HP is Option C.

Fig. 2: Comparison of hourly profiles for district heating demand, electricity demand, and wind production, applied for single year analysis in all models. Top left: District heating hourly demand fluctuations and load curve. Top right: Electricity demand hourly fluctuations and load curve. Bottom left: Off-shore wind production hourly fluctuations and load curve. On-shore wind production hourly fluctuations and load curve..

Fig. 3: Relative results for Alternative Scenarios compared to Reference Scenarios. Top left: Changes in primary fuel consumption excl. renewables other than biomass. Top right: Change in CO2 emissions. Bottom left: Change in total operational costs. Bottom right: Change in net electricity exports.

Table captions

Table 1: Authenticity evaluation of 3E models considered for analysis.
Table 2: Key assumptions for 2010 reference scenarios.
Table 3: Key results for 2010 reference scenarios.



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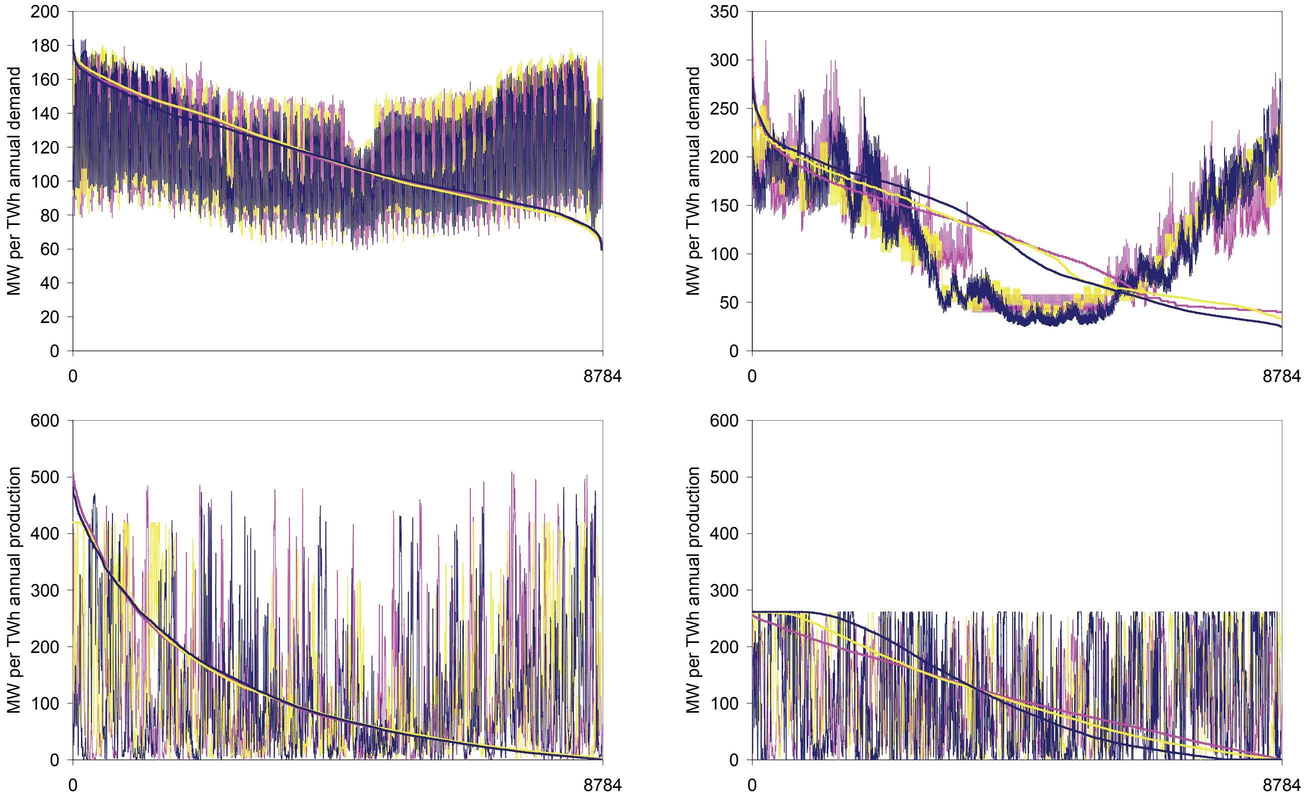

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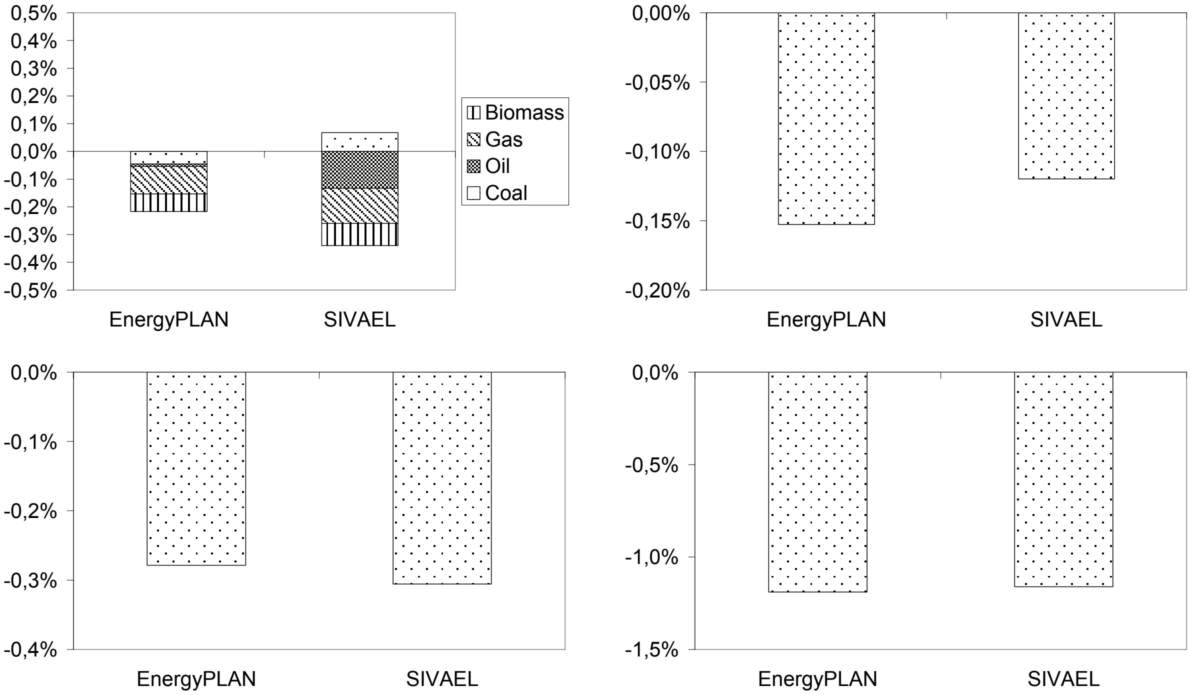

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Table 1: Authenticity evaluation of 3E models considered for analysis.

	EnergyPLAN	SIVAEL	RAMSES
Complete system scope	50%	25%	100%
Bottom-up Top-down integration	10%	25%	50%
Macro-economic consistency	25%	0%	75%
Combinomics**	50%	25%	75%
Micro-economic decision model	Aggregate LC††	Plant LC	Plant LC + MP‡‡
El. price-demand feed-backs	Medium	Low	High
Equilibrium market place simulation	Low	Low	High
Level of plant or entity detail			
- Demand	Low	High	High
- Transmission and exchange	Medium	High	High
- Storage and relocation	Low	Medium§§	Low
- Conversion	Low	High	High
- Resource	Low	High	High
Level of grid details			
- District heating grids	No	Yes	Yes
- Power grids	No	Yes	Yes
Software interface	Text file database, Delphi engine and front end	Oracle database, Oracle, Fortran engine and front end	Excel database, Visual Basic engine and front end
Proprietary	Free compiled version with available data	Free open source version, data limits	Yes
Documentation	Yes	Yes	Yes
Developer(s)	1(+10)	1(+2)	1(+1)

** Evaluation of economic interactions; a "who wins, who looses" evaluation considering relevant economic entities, in the current evaluation model being developed, this is in the form of a welfare economic evaluation of costs and benefit for possibly individual economic entities within each of the major economic areas: fiscal costs, economic costs, financial costs, balance of payment costs, and employment sectors; financial costs possibly by entity, and certainly in respect of whether costs incurs on a business level, even investor level, or private consumer level.

†† LC: Least-Cost.

‡‡ MP: Market Power.

§§ Detailed techno-economic optimization for each plant including thermal storage

Table 2: Key assumptions for 2010 reference scenarios.

		EnergyPLAN	**SIVAEL**	**RAMSES**
Electricity demand[***]	TWh	36,81	39,59	36,81
District heating demand	TWh	37,08	38,54	37,08
Thermal storages	GWh	20,9	20,9	-[†††]
On-shore wind	MW / TWh	2935 / 6,14	2935 / 6,91	- / 8,68
Off-shore wind	MW / TWh	776 / 2,55	776 / 3,03	
District heating boilers	TWh	5,04	2,38	5,04
Industrial CHP	MWe / TWh-q	2165 / 17,65	2165 / 17,65	- /0,73
Distributed CHP	MWe / TWh-q			- / 30,50
Central CHP	MWe / TWh-q	8110 / 18,22	8110 / 18,22	
Condensing plants	MWe / TWh	8110+1190 / -	1190 / 2,45	- / 11,51
Nord Pool spot price[‡‡‡]	DKK / MWh	355	355	287
Fuel prices	DKK/GJ			
- Coal (power plants)			15,8	
- Fuel oil			34,2	
- Gasoil			59,9	
- Natural gas (power plants)			39,4	
- Natural gas (CHP)			46,7	
- Biomass			30,6	

Table 3: Key results for 2010 reference scenarios.

Results		EnergyPLAN	SIVAEL	RAMSES
Net electricity exports	TWh	10,9	15,5	13,6
Domestic market price[§§§]	DKK / MWh	266	355	-
Primary fuel consumption[****]	TWh	110,6	124,5	93,1
- Coal	% of total	49 %	60 %	46 %
- Oil	% of total	5 %	2 %	6 %
- Gas	% of total	26 %	25 %	28 %
- Biomass	% of total	19 %	12 %	21 %
CO2 emissions	Mill. ton	26,2	33,4	21,3[††††]
Fuel and var. O&M costs[‡‡‡‡]	Mill. DKK	11688	12826	-
Net electricity exports benefits		3076	7918	
Total operational costs[§§§§]	DKK	8612	4908	-

[***] Excl. exchange, but incl. grid loss.

[†††] Not available in the sense that value are most likely specified, however not accessible for scope of this paper.

[‡‡‡] Weighed average electricity price.

[§§§] According to which production units in aggregate plants are dispatched.

[****] Excl. renewables other than biomass, district heating and electricity sectors only.

[††††] Calculated from fuels, not explicit in available results.

[‡‡‡‡] Excl. benefits from power exchange. Excl. CO2 shadow costs.

[§§§§] Incl. benefits from electricity exports. Excl. CO2 shadow costs.

6 Heat pumps (AAU)

6.1 Key findings

The purpose of this paper has been to explore options for using large-scale heat pumps for the purpose of relocation. Particular attention should be given to the following 5 key findings:

1. Large-scale compression and absorption heat pumps are competing options for increasing the overall efficiency of CHP production by utilizing condensed flue gas. In concurrent operation CHP plants with heat pumps (CHP-HP plants) reaches overall plant efficiencies of above 100% (based on LHV). While absorption heat pumps are currently better positioned market-wise and the preferred short-term choice by investors, only compression heat pumps may potentially serve the purpose of relocation.

2. While forcing CHP producers away from fixed tariffs onto market conditions (spot market and regulating market) has already effectively solved the problem of critical excess electricity production in the Danish energy system, additional instruments are being introduced to stimulate relocation-driven use of electricity. However, the L1417 instrument introduced in 2006 that reduces energy and environmental taxation on electricity use for district heating production at CHP plants without concurrent power production penalizes efficient use of electricity and excludes the use of compression heat pumps in favour of less efficient electric boilers.

3. In this paper, we are introducing the 1st generation CHP-HP Cold Storage (2007-2012) concept, that integrates CHP and heat pumps (HP) using heat recovered from flue gasses as the heat pump's heat source, storing this heat in a "cold storage" allowing for flexible and integrated operation of CHP unit and heat pump. The CHP-HP Cold Storage concept is the most effective CHP plant principle around, and would effectively stimulate a flexible and relocation-driven operational praxis in distributed generation. Furthermore, it implies a breakthrough for transcritical heat pump technologies and a first step towards the 2nd generation CHP-HP Cold Storage concept (2010-2015) that introduces supplementary low-temperature heat sources, like ground-source, allowing for greater flexibility, and higher HP production rates.

4. However, current taxation instruments, at least in Denmark, makes it difficult for CHP plants to opt for the CHP-HP Cold Storage concept despite its' system-wide benefits. Compared to the in-flexible CHP-HP option with mechanical drive compression, CHP-HP Cold Storage with electrical drive compression currently results in annual financial cost savings that are lower for mechanical drive. In a specific case, for a CHP-plant currently on triple tariffs, both options will be subject to financial payback periods of 10 years or more. In conclusion, our assumptions about efficiencies, investment costs, prices shows that are it is likely that no break-through incentives in the current market place for large-scale heat pumps serves the purpose of relocation.

5. Aalborg University recommends for the Danish Parliament to allow for the compensation of energy and environmental tax of up to 10 % of self-produced electricity for use in compression heat pumps producing district heating (the 10%-instrument), which would be a targeted and suitable incentive for replacing current un-flexible distributed CHP plants with relocation-oriented 1st and 2nd generational CHP-HP Cold Storage plants, supporting higher penetration levels of wind power and CHP in the energy system.

6.2 Heat pumps and the principle of relocation

In February 2003, the Danish Ministry of Finance announced that a cost-effective climate strategy for Denmark [1] should be based not only on the continued build-up of wind power capacity (for what it is worth), but also include the penetration of large-scale heat pump projects ”substituting” combined heat and power production. MoF’s initial assessment indicated a potential of 1,5 mill. ton of CO2 per year from 2012 at an economic CO2 shadow cost of DKK -60 (negative sixty) per ton of CO2 for decentralized CHP, and 5,0 mill. ton of CO2 per year at an economic CO2 shadow cost of DKK 250 for centralized CHP, i.e. a combined CO2 reduction potential of 6,5 mill. ton per year, or about 13% of the Danish energy sector’s CO2 emissions in 2002.

The appropriateness of such strategy is backed by more recent assessments by Aalborg University [2] which concludes that the introduction of large-scale heat pumps is a feasible option for sustaining an energy system with fluctuating electricity supply (CHP and wind), and quite recently also by the Danish Board of Technology [3]. This and other research introduces the principle of relocation and provides theoretical energy balances and cost assessments that involve electricity use for heat production, even substantiating comparative preference to heat pumps over electric boilers.

In December 2006, the Danish system grid authority (energinet.dk) announced awarding Aalborg University, EMD International, and Danish Technological Institute DKK 11 mill. for a full-scale demonstration project that attempt to exploring the feasibility of integrating a large-scale heat pump using CO2 as working fluid with an existing distributed CHP plant.

The analyses includes with this paper relates to concepts of integrating large-scale heat pumps with CHP plants in general, and to the concept of CHP-HP Cold Storage in particular.

6.2.1 The principle of relocation

High penetration levels of intermittent energy resources and combined heat and power (CHP) plants require innovations with respect to storage and relocation, i.e. system flexibility by storing energy or by bridging energy carriers [4]. This paper explores large-scale heat pumps as a relocation technology.

Figure 6-1 illustrates the principle of relocation in a 2nd generation sustainable energy system. The heat pump provides cooling and heat, using either mechanical or electrical drive to produce the required work.

While this paper focuses on the application of large-scale heat pumps used for heating purposes in district heating and industry, it will initially review the main principles and technology applications with respect to the principle of relocation.

6.2.2 Early modern large-scale heat pumps

In 1980, the world’s largest compression heat pump was established in Frederikshavn, Denmark. The 10 MWq heat pump was powered by a diesel generator, using sewage discharge as the low-temperature heat source, and supplying district heating to the municipality. Around the same time, Ronneby Municipality, Sweden, installed a 0,5 MWq diesel-powered compression heat pump to supply heating to 55 individual houses. This heat pump was using ambient air as the low-temperature heat source.

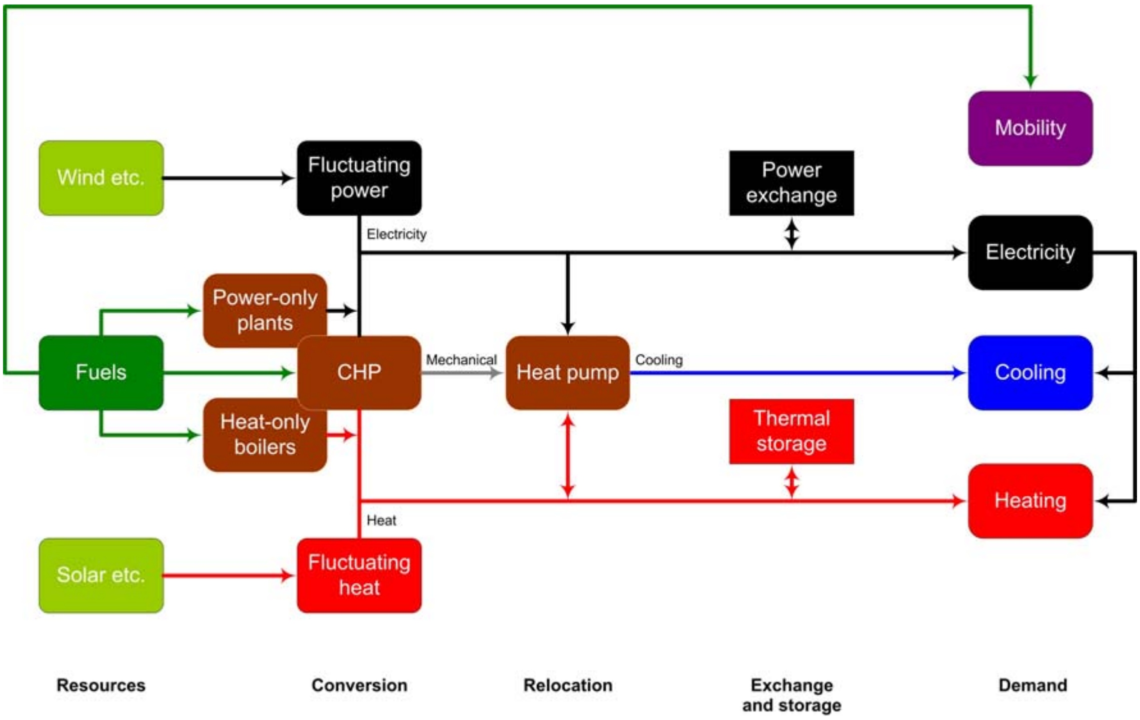

Figure 6-1: 2nd generation sustainable energy system introducing relocation and thermal storage for added operational flexibility

Both experiments were later terminated due to operational challenges. In 1987, the Frederikshavn heat pump was replaced by a natural gas fired CHP plant, and in 1993, the Ronneby heat pump was replaced by a wood-fired boiler. While these projects turned out to be long-term misfits, valuable experiences for future large-scale heat pump systems were produced:

1. The delivered heat should meet the actual needs of the heat takers. In Ronneby, no supplemental heating supply in a low-temperature district heating design with a 60°C plant temperature did likely not satisfy consumers.[6]

2. The heat pump's integration with the operational profile of other elements in the system of operation should be carefully assessed. In Frederikshavn, the prioritized district heating production from the local MSW plant severely restricted the operational space for the heat pump.

3. The design efficiency should carefully match the operational efficiency. In Ronneby, the design COP of 2,0 turned out to be less than 1,6 under actual long-term operation. In Frederikshavn, the actual operational COP of 1,8 was however according to design.

4. The potential threats from using particular working fluids should be carefully assessed. Both Frederikshavn and Ronneby were using the most aggressive ozone depletion and global warming potent cooling liquids (R114 and R12)[7] in complex mechanical driven heat pump systems. In fact, Frederikshavn had particular problems with leaking sealings [5].

[6] My hypothesis.
[7] R12, dichlorodifluoromethane, ODP: 0.95, GWP (100): 10,600; R114, dichlorotetrafluoroethane, ODP: 0.70, GWP (100): 9,800.

5. Particular technical challenges points to flue gas cooling heat exchanger corrosion and leaking sealings.

6. None of these heat pump applications would fit well within a 2nd generation sustainable energy system as they are mechanically powered and do not provide any significant flexibility.[8]

The large-scale plants in Frederikshavn and Ronneby represent an early phase of modern heat pump technology application for district heating purposes. Much has happened since 1980, most notably the nation-specific widespread dissemination of individual heat pumps with supplemental electric heaters, in the US and Japan often combined with A/C, the integration of large-scale heat pumps with combined heat and power plants, including MSW plants, in Sweden and Denmark, and the application of large-scale heat pumps for the utilization of low-temperature geothermal resources.

Sweden is particular rich with past and present case studies; large-scale heat pumps with heat capacities between 5 and 40 MW are found in Stockholm, Gothenburg, Solna, Örebro, Borlänge, Eskilstuna, and Malmö, using sea water or purified sewage water as low-temperature source. In Lund, Sweden, a large-scale heat pump utilizes low-temperature geothermal water.

6.2.3 Selected existing large-scale heat pump applications

In fact, Sweden is the dominant European arena for heat pumps, both in terms of individual and large-scale heat pumps for district heating. In 2005, 100,000 individual units, mainly ground-source or rock-source, were installed, or about one third of the total number of units sold in the European market for individual heat pumps. And in 2004, 12% of Sweden's district heating production was supplied by heat pumps operating at an average COP of 3,5[9] [6].

As such, it is not surprising that the world's largest district heating compression heat pump is located in Sweden, in the town of Umeå, where it has been in operation since September 2000. The 3,4 MWe heat pump uses R134a for working liquid and is an integrated component of a 15 MWe CHP plant that uses wood and industry waste for fuel. The heat pump utilizes condensed flue gas, and delivers heat at an output temperature of 70°C, which is subsequently heated further by turbine condensation to a grid delivery temperature of 105°C. A rather low 10 degree temperature lift allows for an average COP of about 4,0. The heat pump can only be operated concurrently with the CHP plant, reportedly raising the overall efficiency from 94% (without heat pump) to 107% (with heat pump) based on the lower heating value.

But other significant large-scale heat pumps applications are found in the Netherlands, in Norway, and in Denmark.

In Swifterbant, the Netherlands, what is probably the largest ground-source (non-geothermal) heat pump system in operation, 10 couple ground-source heat pumps supplies 79 houses with heating at an average COP of 2,2. Supplementary individual in-house heat pumps are used to supply hot tap water.

In Trondheim, Norway, a large shopping center is cooled and heated by a heat pump system that during the heating period uses the cooling distribution system of a telecommunication centre

[8] Innosys, who designed a natural gas powered heat in Ejby in 1984, during a period of evaluation in 1997 said that the major experience from operation is that the heat pump should preferably be split into an electricity producing part, and an electricity using heat pump.

[9] It is unclear to me whether absorption heat pumps integrated with CHP are included in these statistics, and if so, how. Likely, they are not included.

next-door as the heat source. In the summertime, the heat pump operates mainly for cooling, during which excess heat is distributed to pre-heat sanitary water in a neighbouring hotel. The COP for heating is 3,5.

The last application includes here is Vestforbrændingen, Denmark, an MSW plant, which in December 2006 began operating a flue gas condensation system with two absorption heat pumps.[10] The plant extracts 8,3 kg of steam per second at 163°C to produce 32-43 MW of district heating, equivalent to a COP of 1,9-2,5[11]. While the applied principle has not focused on adding any relocation-driven flexibility to the operation of the plant, it does in principle allow for the extracted steam either to be used for electricity generation[12], or for the heat pump.

These four large-scale heat pump applications represent the variety of the currently best available technologies in large-scale pumps. However, none of these applications provides any flexibility with respect to relocation-driven use of electricity.

6.2.4 Relocation-relevance of heat pump principles and technology applications

In conclusion, existing large-scale heat pump applications are not operated or possible to operation according the principle of relocation.

While an average COP of 3,5 suggest for Swedish heat pumps to be mainly closed-cycle compression systems, various heat pump principles are applied for district heating, individual heating, and industrial purposes.

Table 6-1. reflects on the likely relevance with respect to the principle of relocation of various heat pump principles and technology applications.

Transcritical compression heat pumps that allows for the operation of heat pump with no supplemental heat production (temperature lift), allowing production to thermal storage, is arguably the most promising heat pump technology awaiting application.

The question for researchers and practitioners is how large-scale heat pumps are better designed for the optional purpose of relocation, while assessing the comparative consequences of competing concepts for doing so. The research at AAU is focusing on a particularly promising candidate in this respect; the CHP-HP Cold Storage concept, introduced below and assessed preliminary, which utilizes the principle of transcritical operation.

[10] While the absorption principle is not an obvious choice with respect to the principle of relocation, as explained later in more detail, it is important to include here, as it is a major alternative option for utilization of flue gas condensation, the relevance of which will appear from the introduction of the CHP-HP Cold Storage below.

[11] Energy value of extracted steam can be made a matter of interpretation. In this case, the COP is calculated from the enthalpy of evaporation of the extracted steam, which, at 2 GJ per ton at 30 tons per hour equals 60 GJ, or 16,7 MWh.

[12] At the cost of decreasing overall plant efficiency.

Table 6-1. *Heat pump principles and applications, and relocation relevance.*

System	Applications	Efficiency	Relevance
Closed-cycle compression	Applied for production of heat/ cooling in industry and for district heating/cooling. Maximum output temperature given by working fluid. For ammonia and other non-transcritical working up to 70 ºC. Transcritical operation using CO2 allows for exit temperatures up to 120ºC.	Typically from 1,5 to 5,0 dependent on temperature lift and the nature of the low-temperature heat source.	Highly relevant, in particular with respect to transcritical operation, e.g. using CO2 as working fluid, enabling output temperatures that allows for the operation of heat pump with no supplemental production, allowing production to thermal storage.
Absorption	Applied either as heat pump or heat transformer. As heat pump, with water/lithium bromide as working pair, output temperatures up to 100ºC, temperature lift up to 65ºC. New technology (two-stage) up to 260ºC and higher temperature lifts and COPs. Limited use of drive energy. Heat transformers with no external drive energy, up to 150ºC, lift 50ºC. Widely applied for heat recovery in refuse incineration plants in Sweden and Denmark.	Typically from 1,2 to 1,4 for heat pump operation according to IEA (obviously the principle for the calculation the COP is open for translation, as mentioned above).	Relevant for further investigation, however limited drive energy is applied, or not at all. Allows for increased flexibility in plant operation due to increases in heat production. A widespread alternative to closed-cycle compression heat pumps in terms of cost-effective heat recovery, resulting in very high overall plant efficiencies, but without any relocation potential.
Adsorption	Applied as heat pump, e.g. by adsorption of ammonia into active carbon [7] or water into silica gel.	?	Highly relevant for further investigation, but only with respect to the principle of chemical storage of heat, not for relocation.
Stirling or Stirling-Vuillumier	Multifunctional heat pumps, often heat assisted, using gas-engine drives.	2-2,4 for gas-engine drive [8]. Possibly 3,0-4,0 for electric drives.	Highly relevant alternative to closed-cycle compression system. Currently few practical experiences from large-scale operation, mainly used for cryogenic cooling systems in which Stirling excels.
Vapour recompression	Vapour is compressed to a higher pressure and temperature, and condensed in the same process giving off heat. No evaporator, no condenser, small temperature lift (from 70-80ºC to 110-150ºC, up to 200ºC). Typically H2O as working fluid.	COPs of 10 to 30.	No immediate relevance, though systems may be redesigned for electrical work rather than integrated industrial mechanical work, allowing for load-shifting.
Reverse Brayton	Recovering solvents from gases. Solvent loaden air is compressed, and then expanded. The air cools through the expansion, and the solvents condense and are recovered.	N/A	Not relevant, does not serve any primary heating or cooling purposes.

6.3 CHP-HP Cold Storage

The innovative CHP-HP Cold Storage concept (CHP-HP-CS) provides a solution to problems previously faced when applying large-scale heat pumps in district heating. Furthermore, the concept provides relocation by allowing for greater flexibility in plant operation, allowing for efficient and flexible use of electricity for heat production.

In CHP-HP-CS, low-temperature heat recovered from flue gasses is recovered and stored when the CHP unit is in operation. The recovered heat stored in the cold storage is used as heat source for a transcritical compression heat pump, which is operational at very high COPs due to the relative high temperature level of the heat source and available for operation even without the CHP unit operating. When the heat pump operates it generates cold water for subsequent flue gas cooling and condensation. Temperature levels of cold storage will be in the range of 20-60°C, possibly integrated with the thermal storage, then operating in the range from 20-90°C (Figure 6-2).

With respect to the operation of a heat pump without concurrent operation of CHP unit or supplementary heat production, it was previously not possible reaching the required exit temperature for district heating, which is typically above 80°C. With a transcritical heat pump using CO2 for working fluid, a technology successfully developed at Danish Technological Institute [9] being marketed through start-up company Advansor [10], this problem is solved in the CHP-HP-CS concept.

Aalborg University, EMD International, Danish Technological Institute, and Advansor join forces in a full-scale CHP-HP-CS demonstration project funded by Energinet.dk, the Danish TSO, to be implemented during 2007-2008.

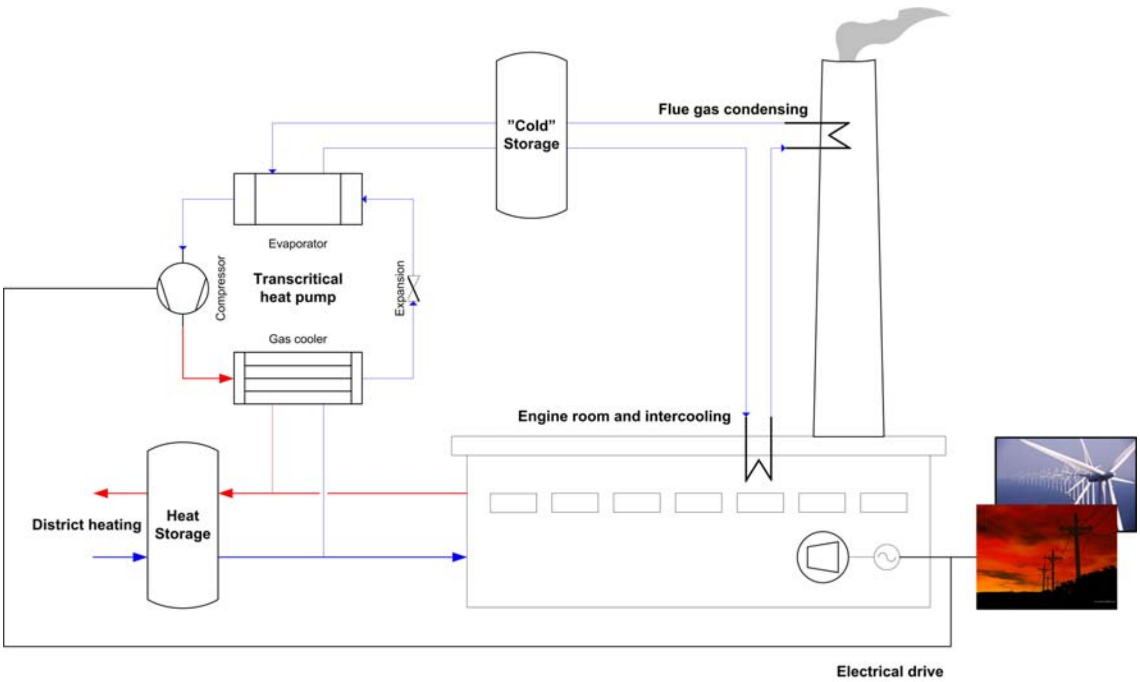

Figure 6-2: 1st generation CHP-HP Cold Storage concept for utilization of heat recovered from flue gasses, concurrent operation AND relocation possible (i.e. operation of heat pump unit or CHP unit).

Table 6-2. *Techno-economic datasheet for CHP-HP Cold Storage*

	Status	Scenario assumptions	
	2006	**Low penetration**	**High penetration**
Working fluid	CO2		
Electric capacity	Up to 10% of installed CHP electricity generating capacity		
Heating capacity	Around 30% of installed CHP heating capacity		
COP	3,7	3,8	3,9
Investment costs[13]	DKK 19,5 mill. per MWe	DKK 19,5 mill. per MWe	DKK 15,0 mill. per MWe
O&M costs	0[14]		
Life time	20 years	20 years	25 years

Techno-economic research and results have been excluded from this paper due to limitations of space, but may be found in Blarke [4,11,12], articles all of which are acknowledging the DESIRE project.

6.4 Instruments for promoting relocation in distributed generation

The first step for introducing relocation and increasing the operational flexibility in an energy system with a high level of penetration of CHP and wind power like the Danish has been gradually to force decentralized power producers to operate on market conditions.

By January 2005, all Danish CHP plants above 10 MWe (49 plants @ 1.220 MWe) had moved away from fixed tariffs to market conditions (spot market, regulating market). Immediately, this effectively solved the problem of critical excess electricity production.[15] In January 2007, all Danish CHP plants between 5 and 10 MWe (74 plants @ 438 MWe) are being moved to operate on market conditions. All plants below 5 MWe (684 plants @ 713 MWe) may continue on triple tariffs at least until 2015. As of January 2007, 144 plants will be operating on market conditions, representing about 70-75 % of total electricity generating CHP capacity.

As the introduction of market conditions have effectively made the integration of CHP and wind power more practical, additional instruments are required in preparing for the further penetration of wind power, and substitution of non-CHP utility units.

In December 2005, the Danish Parliament agreed on Law L1417 [13] that introduces incentives to promote the relocation-driven use of electricity. L1417 introduces changes to existing energy and environmental taxes, most notably with respect to the taxation of the use of electricity for district heating production, and is mainly intended to stimulate the introduction of electric boilers at existing CHP plants.

Prior to L1417 any use of electricity for heating production, also self-produced electricity, was subject to an energy and environmental tax of DKK 0,665 per kWh.[16] With L1417 this tax is reduced to DKK 50 per produced GJ of district heating[17], but applies on the condition of no

[13] Based on case study, plant specific: HP unit 60%, Cold Storage: 14%, generator: 2%, optional stainless stack kernel replacement: 10%, optional LP heat exchanger replacement: 14%.

[14] Meromkostning ift. eksisterende kraftvarmeproduktion. Baserer sig på en antagelse om at varmmepumpeanlæggets D&V omkostninger dækkes af D&V besparelser for kraftvarmeenheden.

[15] According to information obtained from energinet.dk in November 2006 (Jens Pedersen).

[16] DKK 0,576 per kWh (energy tax) plus DKK 0,09 per kWh (CO2 tax).

[17] DKK 45 per GJ (energy tax) plus DKK 5 per GJ (CO2 tax).

concurrent production at the CHP unit. The instrument's particular condition of no-concurrency illustrates the operational strategy hereby introduced for balancing wind power and CHP: on demand, reduce CHP-production, while increasing relocation-driven use of electricity.

However, the mischief in this respect is that L1417 while promoting the relocation-driven use of electricity also penalizes the efficient use of electricity. As the new energy and environmental tax is calculated on the basis of district heating production, not on electricity use, the more efficient use of electricity, the higher the resulting tax per kWh of consumed electricity. While the tax for electricity used in an electric boiler is reduced by 73% (from DKK 0,665 per kWh to DKK 0,18 per kWh), the tax for electricity used in an efficient compression heat pump is reduced only by 5% (from DKK 0,665 per kWh to DKK 0,63 per kWh)[18].

In result, the revised energy and environmental taxation scheme sustains the current situation for large-scale compression heat pumps, that, if found applicable, will, if compression heat pumps are favoured at all, result in the choice of mechanically driven compression, allowing only for concurrent operation of CHP-unit and heat pump. This result in fuel savings and high efficiency plant operation, however mechanical driven compression does not allow for relocation-driven use of electricity, as electrical drive potentially does. In fact, even for similar operational strategies, electrical drive is "disallowed" by existing energy and environmental taxation system.

In April 2006, communication with the Central Customs and Tax Administration is opening for the possibility that tax on the use of electricity in a CHP-HP-CS concept may be subject to principle that in praxis will burden a kWh of electricity used in a heat pump similar to that in an electric boiler.

However, looking forward to concept that includes external heat source, what kind of instrument would effectively stimulate the introduction of designs in distributed production that allows for relocation? Aalborg University is arguing for the introduction of an instrument that will allow for various CHP-HP concepts in the short-term future to be established using electricity-driven compression: the 10%-instrument. Aalborg University recommends for the Danish Parliament to allow for the compensation of energy and environmental tax of up to 10 % of self-produced electricity for use in compression heat pumps producing district heating.

The 10%-instrument would stimulate not only a more efficient CHP production for concurrent operation of CHP unit and heat pump, but also, in combination with L1417, support the relocation-driven use of electricity. Under the current Danish policy climate, the strength of this instrument is that it is arguably neutral with respect to fiscal revenues, as mechanical-driven and electrical-driven compression results in identical operation for concurrent operation of CHP unit and heat pump. Both options works similar to reducing electricity production, while increasing heating production, often reaching overall plant efficiencies of above 100 % (based on Lower Heating Value).

However, in praxis, the issue of fiscal revenues and other impacts is somewhat trickier, as the introduction of electrical-drive compression intentionally opens up for other concepts.

6.5 Conclusion and perspectives

Large-scale heat pumps should not be regarded an efficient alternative to electric boilers, but rather as an integrated system component that contributes to increased operational flexibility. In the future, large-scale heat pumps may be an efficient alternative to combined heat and power

[18] For a COP of 3,8.

production, but in the short to medium term to solution is to research options that integrate large-scale heat pumps with distributed generators, maintaining the benefits of cogeneration, while allowing for balancing intermittent resources.

From a review of large-scale heat pump applications, it is found that large-scale heat pumps are never an off-the-shelve turn-key solution, but always appears as a customized industrial component being integrated with other plant components. There is a particular important reason for this: heat pumps utilizes a low-temperature heat source, either recovered heat from flue gasses, ground or rock-source, solar, sea, lake, waste water, ambient air, cooling demand, or intercooling. The availability of low-temperature heat source is highly localized. The specific availability and temperature level of this localized low-temperature heat source is used to settle for a particular operational design and resulting COP. As such, the COP may range from as little as 1 to above 5 depending here mainly on inlet temperature to the evaporator, i.e. the temperature level of the heat source.

The CHP-HP-CS concept is a solution to many of the problems associated with integrating large-scale heat pumps in to the energy system, while increasing the flexibility required for greater penetration levels of CHP and wind power. Targets could be to set to achieve market penetration for this generation concept during 2007-2012.

However, the 1st generation CHP-HP-CS may be seen only as the first step towards the 2nd generation CHP-HP-CS concept that introduces supplementary low-temperature heat sources, like ground-source, and even combines heat pumps and electric boilers. Targets could be to set to achieve market penetration for this 2nd generation concept during 2010-2015, *Figure 6-3*.

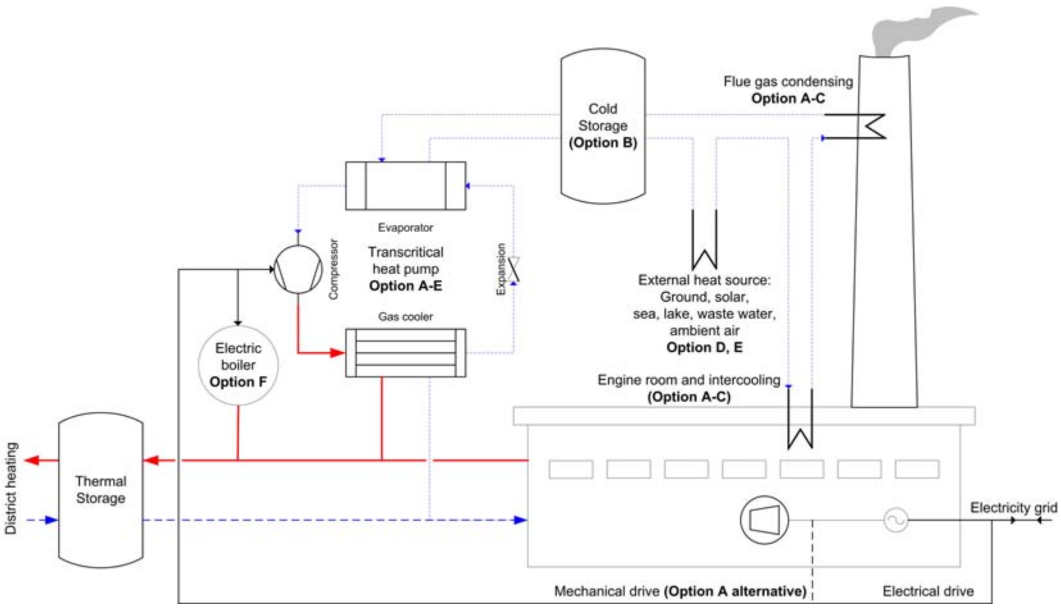

Figure 6-3: *2nd generation CHP-HP Cold Storage concept for utilization of condensed flue gas AND optional low-temperature source, like ground-source, possibly also combining heat pump and electric boilers.*

Energinet.dk, the Danish TSO, is sponsoring a DKK 11 mill. demonstration project for a CHP-HP-CS demonstration plant being in operation no earlier than by December 2007. DESIRE partners Aalborg University and EMD will particular be involved in further developing system and project modeling methodologies under the project.

From dusk till dawn

An essay about how the climate crisis has come to define sustainable energy in the context of the Danish experiment

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May 2008

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1. The problem – and how to deal with it

CO2 increases anywhere are a threat to the future of civilization everywhere, Gore in Oslo 10/7/07

Stardust. That's what it was. Originating from exploding giant stars, supernovas, 4,567 billion years ago, a cloud of stardust was here long before Kilroy, and the stardust collapsed under its' own weight to form the Sun at the cloud's centre. And in a chaos of dust and gasses, a glowing hot rock appeared, and perhaps ... well, perhaps an icy comet hit this rock only to evaporate. For all we know, in the beginning, it rained. And for 800 million years there was no land in sight, only water. And in this sea, life on earth began.

In 2003, Professor Minik Rosing from the University of Copenhagen announced the discovery of what is the earliest undisputed evidence of life on Earth. Trace of cyanobacteria in a 3.7 billion-year-old rock from Greenland tells us that life had evolved quickly to harvest the Sun's light by photosynthesis.

In hindsight, the evolutionary path seems pretty straightforward. Cyanobacterias and algae established a basis for atmospheric oxygen, and during the Palaeozoic Era life really took off. Initiating in the Vendian period 650 million years ago up until the beginning of the Mesozoic Era 248 million years ago, and with particular speed during the carboniferous period about 354 to 290 million years ago (anyway long before T. Rex), plants and algae were dominating organic life forms, and they flourished.

Over thousands of millenniums, plants and algae in lakes and swamps would sink down to form layers of dead organic material. Time, pressure, and heat converted this material to what we know as coal, oil, and gas. And at sea, early plankton would sediment similarly to produce oil and gas.

So far, no problem. But as it turns out, early life on earth would return to haunt modern man.

1.1 Looking for trouble

Energy. That's what life is all about. As early primates would leave the forests to explore the open grasslands about 8 million years ago, with homo ergaster branching out about 2 million years ago, they adapted to an environment, which provided plenty of opportunities for experiments. The basic need for energy (food, heat, light) may have been the single most important driver in bringing about the earliest tools and the controlled use of fire. Stone tools may date back as far as 2,6 million years, while some evidence indicate that man, possibly Homo Erectus, had fire under control already 1,5 million years ago.[1]

The environment would offer many opportunities for man to discover his nature, and controlling energy came to be a crucial comparative evolutionary advantage. When Homo Sapiens branched out 250,000 years ago, tools and fire was already being mastered by Homo Neanderthalis, Erectus, and Rhodesiensis. But Homo Sapiens would take human creativity much further as faced by opportunity. Ancient Sumerians are known to have used crude oil from leaking oil fields in lamps to provide light. And 3,000 years ago, man would try using coal for smelting copper[2]. "Burning rocks" and "black water" allowed man "to do things", and little conscious, life was well on the way to return to the stars.

This learning to control the environment, this quest for energy, land, and technology, is it a basic instinct of life that provides us comparative advantages for survival and comfort? Or could it be a flawed evolutionary path, which threatens the survival of all primates?

For all we know, cheap and plentiful supply of fossil energy was to become an imperative to human life. And when Drake began pumping oil from rocks beneath his land in Pennsylvania in 1857, first stored in his bath tub, thereby solving the problem of how cost-effectively to extract 300 million year old fossil organic material from inside rocks, early life made a striking re-appearance and quickly came to define modern

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[1] This hypothesis is the result of research made in collaboration between South African researchers Dr Bob Brain and Dr Francis Thackeray of the Transvaal Museum in Pretoria, and researchers at Williams College in Williamstown, US. The oldest undisputed evidence of man's controlled use of fire dates back only 400,000 years.
[2] Fu-shun mine in northeastern China

society in an unimaginable way, even allowing for man to travel into space.

For the last 150 years, man's thirst for fossil energy resources has increased almost exponentially. The world's daily consumption of oil was 84 million barrels in 2005, expected to increase by 38% to 116 million barrels per day by 2030 according to the reference scenario of the International Energy Agency's (IEA) "World Energy Outlook 2006" [1]. The consumption of natural gas was 2.8 tcm in 2004, expected by the IEA to increase by 68% to 4.7 tcm by 2030. Similarly for the consumption of coal, the world consumed 5,6 billion tons in 2004, expected by the IEA to increase by 59% to 8,9 billion tons in 2030.

By nature, fossil fuels are depletable and geographically unequally distributed. In 2005, the proven reserves of oil amounted to 1.293 billion barrels, equivalent to 40 years of consumption[3], the proven reserves of gas amounted to 180 tcm, equivalent to 64 years of consumption[4], while the proven reserves of coal amounted to 909 billion tons, equivalent to 162 years of consumption.[5]

But the depletable nature of fossil energy resources is not a critical problem. Nor is the increasingly costly supply of fossil fuels nothing but an opportunity for competing options, and while these conditions may represent future challenges, they do not constitute any fundamental problem or threat to civilization. And the geographically unequal distribution of oil - 62% of increasingly valuable oil reserves are located in the Middle East – may be a concern for some, but it is certainly no problem to the Saudis.

But we have indeed found trouble, it seems.

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[3] Oil and Gas Journal (19 December 2005). Includes proven oil-sands reserves in Canada.
[4] Cedigaz, 2006
[5] All estimates made for current levels of consumption, not taking expected consumption growht rates into consideration.

1.2 The climate crisis

Air. Many life forms breaths air to obtain the oxygen that reacts with glucose in cells to fuel basic life functions. There is $5{,}3*10^{15}$ tons of air in the atmosphere, made up of 78% nitrogen, 20,95% oxygen, 0,93% argon, 0,038% carbon dioxide, trace amounts of other gases, and a variable amount (average around 1%) of water vapour [2][6]. But carbon dioxide was not always at 380 ppm. In fact, 150 years ago it was only around 280 ppm. What is the reason for this, and what are the consequences?

It has been suggested that human activity is guilty of increasing the share of carbon dioxide in the atmosphere. With a breath of air, humans supplies oxygen to the blood, while removing carbon dioxide from the blood. An exhaled breath of air contains about 17% oxygen and 4% carbon dioxide, and in this way, humans exhale about 0,6 billion tons of carbon as carbon dioxide per year [3]. Fortunately, the act of breathing is not the culprit – but fossil fuel consumption likely is. The carbon and hydrogen content of a fuel reacts with oxygen to produce heat, emitting mainly carbon dioxide and water. It is estimated that human use of fossil fuels in 2006 releases about 8 billion tons of carbon as carbon dioxide into the atmosphere [3].

In March 1954, Charles Keeling from the Scripps Institution of Oceanography began monitoring the concentration of carbon dioxide in the atmosphere with gas analyzers at three locations: Mount Loa in Hawaii, Little America in Antarctica, and La Jolla in California. In Keeling's first paper published in 1960 [4], he presents two tentative hypotheses. The first hypothesis is that the growth of land plants results in seasonal variations in atmospheric carbon dioxide concentration, for example in 1955 dropping from 316 ppm to 309 ppm during the summer months of the Northern Hemisphere, the particular timing due to the much bigger area of growing plants in the Northern Hemisphere than in the Southern Hemisphere. The second hypothesis is that the observed increase in concentration of 1,3 ppm per year is the result of the combustion of fossil fuels, as it matches the estimated carbon dioxide contribution of 1,4

[6] By molar content/volume.

ppm per year at the time. "[O]ne might be led to conclude that the oceans have been without effect in reducing the annual increase in concentration resulting from the combustion of fossil fuel", as Keeling puts it.

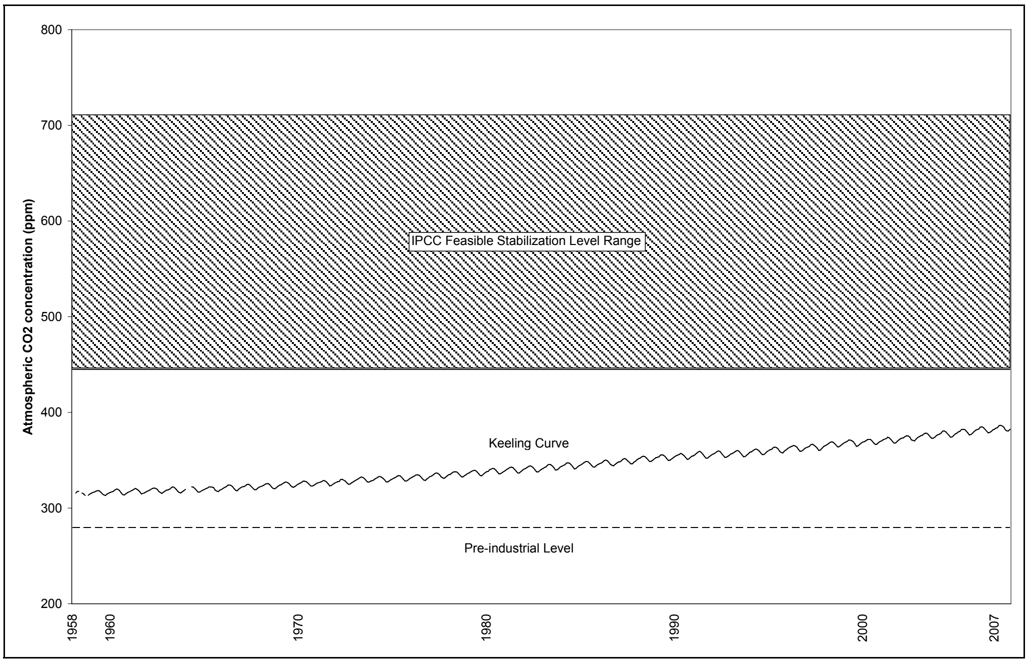

Fig. 1: Atmospheric CO2 concentrations (ppm) from March 1958 to November 2007 derived from in situ air measurements at Mauna Loa, Observatory, Hawaii – the Keeling Curve [5]. Above the Keeling Curve is included 2007 IPCC feasible mitigation stabilization level range of 445-710 ppm for which associated global mean temperature increase ranges from 2-4°C, and GDP reduction ranges from 3% to -0,6% [6]. Below the Keeling Curve is included pre-industrial level of 280 ppm.

Today, climate scientists have developed advanced models that simulates the complexity of atmospheric interactions taking place [7]. Observations have confirmed that the atmospheric CO2 concentration is increasing, and models have confirmed that the combustion of fossil fuels is the main culprit, while also assessing the consequences that increasing levels of atmospheric carbon dioxide may have. In November 2007, the working group I report from IPCC concludes that there is "[...] very high confidence that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of 1.6 W/m^2" [8]. With "very high confidence", IPCC means above 90% probability of occurrence, and with “human activities”, IPCC focuses almost entirely on the combustion of fossil fuels. Concluding on the basis of a series of direct observations, IPCC concludes that the “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level”. IPCC is working to improve our understanding of how human activity influences the climate, and their most current findings sustains that atmospheric CO2 concentration is increasing, in particular due to the combustion of fossil fuels, and that it is leading to global warming with serious consequences for many nations and people.

Fig. 2: Gore's point-of-no-return. A screen-shot from "An Independent Truth" at the point where Gore illustrates that atmospheric carbon dioxide and temperature have been closely correlated for 650.000 years. Screenshot from [9].

In 2006, former US vice president Al Gore helped frame the problem as “the climate crisis”. In a visually most effective move in the Academy Award winning documentary, “An Inconvenient Truth”, Gore presents his point-of-no-return, certainly in his movie, but also in discussions about whether it matters that CO2 levels in the Earth’s atmosphere are increasing. Gore’s chart shows two curves that are closely correlated for a period of 650,000 years. While one curve illustrates the absolute global average temperature, the other curve illustrates the CO_2 concentration in the atmosphere. The curves are based on data obtained from the British Antarctic Survey that have been drilling into the Antarctic ice core for years, reaching more than 3 km below the surface of Antarctica. The temperature curve is then deducted on the basis of a spectrometry of certain isotopes in the ice, while the CO_2 curve is compiled from the analysis of small pockets of air remaining in the ice. Using an industrial truck lift, Gore theatrically establishes the current level of CO_2 concentration, which is at 380 ppm in the atmosphere or around 30% higher than ever before during the last 650,000 years. From present day levels, Gore illustrates that the CO_2 concentration, growing 200 times faster than ever before, is projected to reach about 500 ppm in 50 years, almost 80% above the pre-industrial level of 280 ppm [9,10].

"[F]or their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change", IPCC and Al Gore was awarded the 2007 Nobel Peace Prize. As the Norwegian Nobel Committee concludes their nomination: "[a]ction is necessary now, before climate change moves beyond man's control."

The recognition of this problem, the climate crisis, and the urgency in mitigating the extent hereof, is of fundamental significance to the work undertaken with the thesis. World leaders are buying in to the climate crisis, but setting political goals is perhaps really the easy part. The difficult part is building understanding and wisdom about problems and opportunities, engaging the right people to address opportunity, while attracting the will and power to implement effective solutions. The thesis takes on itself to contribute in the area of this more difficult part. But how may we fundamentally know how to deal with options that intend to solve serious problems, such as the climate crisis? How do we reach an acceptable level of understanding about what would be the rational and responsible thing to do, and how will we act upon this understanding?

1.3 The problem of knowing

“SEVERAL years have now elapsed since I first became aware that I had accepted, even from my youth, many false opinions for true, and that consequently what I afterward based on such principles was highly doubtful,” writes René Descartes in the opening of First Philosophy/Meditation [11]. As Galileo Galilei lay in his deathbed, Descartes would meditate a philosophy that added important elements to the scientific tradition. And while Descartes in Meditations goes on to present doubtful evidence of God’s existence, using only logic, he teaches us an invaluable lesson: to question established truths, to think for ourselves, and most importantly, to be careful and sceptical towards an illusive reality, towards our senses, towards what we may think that we know.

“What’s responsible for the lock-step correlation between these two curves for the last 650,000 years of Earth’s history”? This was for many years the research question for Professor Robert Giegengack of Department of Earth and Environmental Science at University of Pennsylvania, and when interviewed on the Dennis Prager radio show on his findings in the wake of “An Inconvenient Truth”, Giegengack argues that Gore’s point-of-no-return builds on a misinterpretation of data [12]. According to Giegengack’s research, the temperature of the Earth is influenced mainly by variations in the geometry of the Earth-Sun system, and the driving mechanism is exactly the opposite of what Gore claims: It is the temperature that controls the CO2, not CO2 that controls the temperature. Giegengack does not question the likely fact that human activity is resulting in global warming, but he argues that the scientific evidence as presented by Gore to support this hypothesis is fundamentally flawed. What appears so evidently truthful in “An Inconvenient Truth”, being the “point-of-no-return” for Gore’s claim that the climate crisis is a direct effect of increase levels of atmospheric carbon dioxide, may in fact rest upon a misinterpretation.

In Meditations, Descartes realizes that understanding is always incomplete, that only will is complete. This schism – incomplete understanding, complete will - is a cornerstone in planning research, in decision-making, in science, in life. What would be an appropriate approach to planning and decision-making, if we should accept that understanding is never complete? And that wilful decisions and actions, however necessary, may have doubtful or even contradictory consequences to the intentions that lay behind? How could we appropriately deal with uncertainty and risks?

Descartes imagined building for himself a “scientific superstructure” that would allow for a firm and true understanding of phenomenons in nature and philosophy. While such ambition has fuelled the naturalist tradition in science, Descartes teaches us to doubt conclusions presented from reasoning on the basis of sense perception. Kant, inspired by Descartes, brings the synthesis of science and philosophy further, daring humans to reach an understanding by themselves, judging for themselves, while Hegel, inspired by both Descartes and Kant, returned to Descartes in his attempt to creating a philosophical super-structure based on dialectics, and realized that our understanding should include matters of an envisioned past and future.

Descartes, Kant, and Hegel share a similar belonging to a systematic assessment of the problem of knowing that may result in scientific superstructures and general frameworks for reaching understanding. Popper may have shared such vision, while Habermas, Foucault, and Kierkegaard would certainly find such effort arrogant and contradictory to the nature of knowledge. But even if knowledge by nature is evasive, and never becomes better than “as good as it gets”, as Popper would be likely to think, is it arrogant to suggest a superstructure for reaching understanding and acting upon it, if it recognizes the tentative nature of knowledge, the deliberative basis for reason, while bringing light to the interests upon which various rationalities are based?

One of the basic theoretical problems that stir the debate between the great minds of modernity and reason relates to dealing with language, meaning, and concepts of reality. Naturalists, empiricists, realists, pragmatists, and constructivists will certainly contest each other on basics, but what may possibly constitute a common ground for these courses of thought? It seems to me that naturalists and constructivist share at least two common notions upon which to meet: the comparative approach and the rational choice objective [13]. On the basis of these common notions, I have outlined a framework for my research, a super-structure, for dealing with the problems, the objectives, the past, the future, the options, the agents, the interaction, and intentional change. The framework is directed at wilful experiments on the basis of incomplete understanding. I call it the wisdom-generating framework, with inspiration from methodologies in PBL, integrated energy planning, and phronetic planning research [14], having presented elements of the framework in three articles published in 2006-2007: *Interactivity in Planning: Frameworking Tools* [15], *Interactive energy planning* [16], and *Interactive energy planning: Towards a sound and effective planning praxis* [17].

Fig. 3 attempts to capture this suggested planning research process in a single illustration. The wisdom-generating framework is basically very simple, some would say obvious. However, I would like to advocate the understanding that the framework captures what should be, but rarely is, a preferred standard in planning research. The framework is intended to support planning processes in a reality of uncertainty and risks by reminding planners that interventions are intentional experiments that need to be carefully prepared with respect to context, problem, objective, history, baseline, options, consequences, and intentions.

Every intervention is an experiment of intent. Chances for interventions and intentions to be *wise* improve when they are outputs of research activities that answer these questions:

1. What is the problem, and for whom?
2. Where to go (what should be the objective)?
3. Where are we now, and where did we come from?
4. Where are going?
5. What are options for change?
6. Who wins, and who loses – what are the consequences - with respect to these options?
7. What kind of experiment should we do, if anything?
8. What is the intention of this experiment, and how does it influence our objectives?

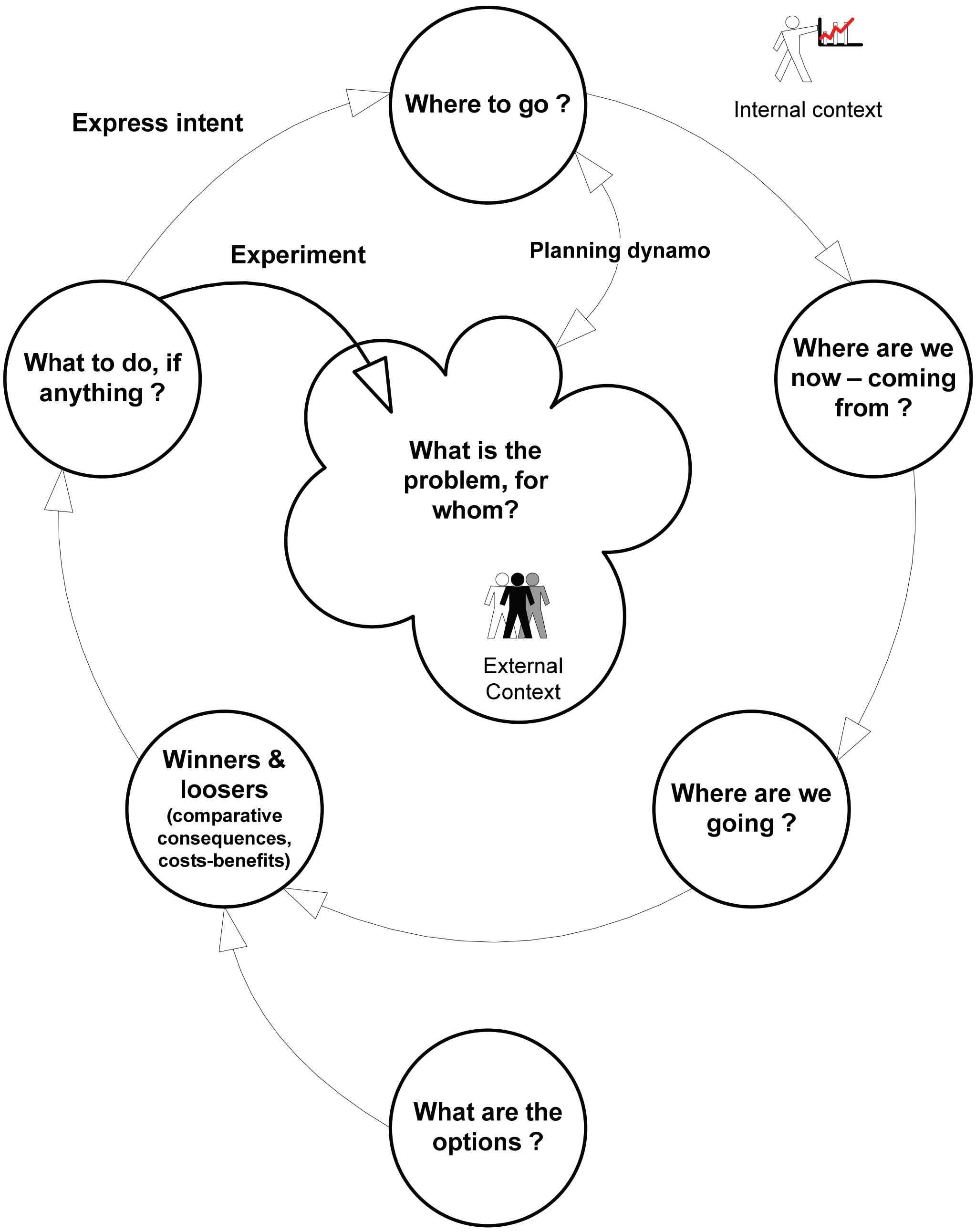

Fig. 3: Intentional experimentation: The wisdom-generating planning process.

The thesis as a whole, with which this essay is published, attempts to complete the planning cycle above, in its main part focusing on assessing the consequences of particular intentional experiments. This essay establishes a contextual basis with respect to questions 1 – 5. Chapter 1 has established the planning dynamo, proposing that global warming is the problem, supposedly to civilization as we know it, and that the objective is to stabilize and ultimately reduce the carbon content in the atmosphere. Also, findings in Chapter 1 suggest that an effective effort would target the energy sector. Chapter 2 takes a look at where we are now, and particularly where we are coming from in the context of the Danish energy sector. Chapter 3 discusses where we are seemingly going with respect to sustainable energy, and what our fundamental options are.

2. A Danish energy context

The Danish carbon dioxide emissions from electricity and heat production is the second lowest among non-nuclear energy systems in Europe, only surpassed by Austria (Fig. 4).

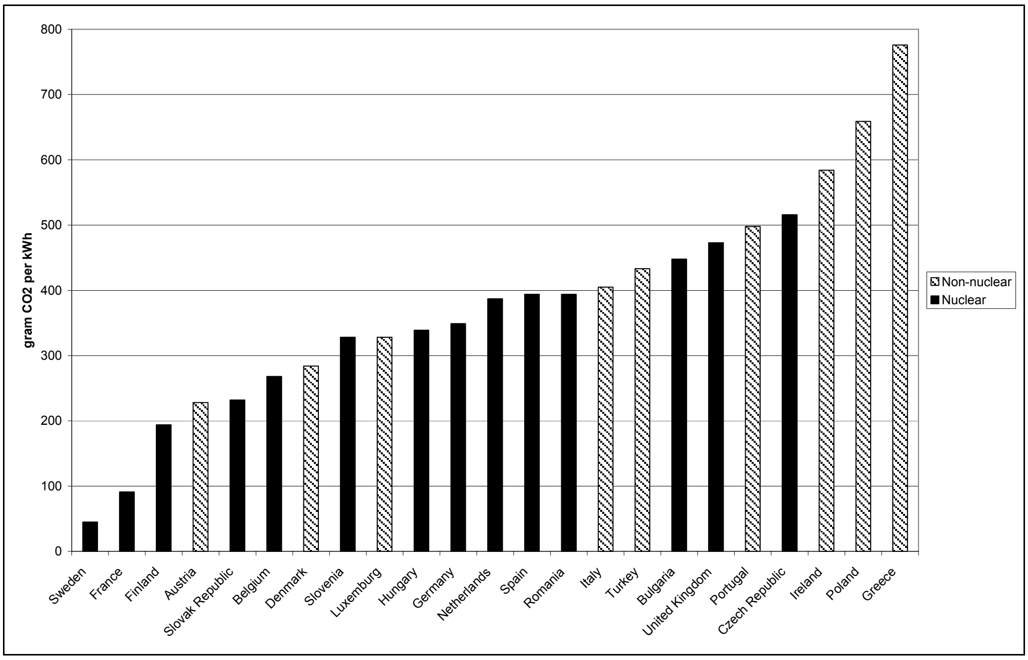

Fig. 4: CO2 emissions in 2005 from fossil fuels consumed for electricity, CHP, and main activity heat plants in nuclear and non-nuclear European energy systems divided by the output of electricity and heat generated from fossil fuels, nuclear, hydro (excluding pumped storage), geothermal, solar and biomass. Both main activity producers and auto producers are included. Data from [18].

The key to understanding the Danish accomplishment is the relatively high exergetic efficiency of the Danish energy system, in particular reached by introducing the principle of cogeneration of heat and power. So far, a domestic integration strategy for large-scale penetration of distributed cogenerators and intermittent wind power has resulted in penetration rates for CHP and wind power in the West Danish energy system that are higher than anywhere else in the world.

2.1 Where are we coming from?

In a text-book article about Danish energy policy and planning, Professor Henrik Lund identifies the oil crisis of 1973 as a starting point for modern Danish energy policy, and describes its development as a partnership effort between Government policy-makers and an engaged civil society dedicated to non-conventional alternatives. In opposition to this partnership, established supply authorities were never eager to support the introduction of new technologies, Lund argues [19].

While I appreciate this important perspective of conflicting interests, the development of Denmark's energy system is a story in its own right, with numerous patterns that may, or may not, say anything about the dynamics of change. Based on events that I have found relevant to include, my attempt to produce a meaningful narrative bears witness to the importance of apparently insignificant details. It is a narrative about the unlikeliness and unpredictable nature of change. But more than anything, the narrative suggest that understanding change requires the appreciation of necessity and opportunity in a flow of decisive moments, and seeing how wisdom arrived from wilful experiments.

My hypothesis is that we may learn something important about changes in the Danish energy system by looking at two historical tracks of events; the so-called success of wind power, and the opposition against nuclear energy. And that we may look to 1985 only for the culmination of events, but that we need to look further back to appreciate the complexity of events that went into making the energy system.

At the same time, this narrative about how sustainable energy came around in Denmark is a good platform for challenging the idea that change comes from above; that it is policy, and political leadership that develops the visions that then grow out into our reality. Henrik Lund points to the crucial importance of energy planning and plans. My experience is that good plans reflect realistic goals anchored in civil society, not nerdy utopias. Good plans are anchored on civil engagement and experiments.

As there is no unambiguous point to begin a narrative about the Danish energy system's developments towards sustainability, let us begin by looking at a product, and a producer, which was recently canonised. How much more blessed can one get? In January 2006, a committee appointed by the Danish Ministry of Culture, argued to include the Gedser Wind Turbine (Danish: Gedsermøllen) among the 12 artefacts in canon for design, arts, and crafts that were chosen to symbolize Danish culture. Their argument was:

"Through many years, Denmark has played a leading part in the evolution of wind turbine technology. This is, among other factors, due to the pioneering work conducted during the development of the Gedser turbine. In the 1950s, it did not yet seem evident that the main energy source in Denmark would be fossil fuels. The country had not yet recovered from the rationing of wartime and nobody could anticipate the enormous energy demand that would arise as a consequence of the growth of the 1960s. Other countries put great efforts into developing hydro power, even the USA, which at that time had abundant oil reserves. Considering this, it is no wonder that a country like Denmark, which did not yet know of the oil and natural gas reserves of the North Sea, made experiments on how to exploit its most abundant resource: wind. The Gedser turbine outdistanced the traditional small windmills [of adjustable narrow vanes] by being the first large turbine which was not blown into pieces by the wind. It represented the first step in the evolutionary process which today results in a series of turbine types both in Denmark and abroad. The next – symbolic – step was the Tvind turbine, which to a whole generation came to represent the dream of sustainable energy. The design of turbines is a work which requires a thorough knowledge of statics and wind, and which shows how design can form part of engineering at its best. The turbines have little by little become a symbol of present-day Denmark; an important part of our culture which meets us at the sea-ward approach to Copenhagen and in many other parts of the country."[20] [7]

The Gedser Wind Turbine (Fig. 5) was developed by Johannes Juul, head of engineering for SEAS, the Zealand electricity company. Juul had just finished building the world's first AC-producing wind turbine at Vester Egesborg on Southern Zealand, and in 1957 he designed and constructed this grid-

[7] Oversættelse af Mette Sørensen, Aalborg Universitet.

connected 200 kW turbine, for many years the largest wind turbine in the world, located near the town of Gedser at the wind rich southern Falster. The design and construction details are worth noting as they characterize the principles of modern Danish wind turbines: 3 blade forerunner, electro-mechanical fantail, grid-connect asynchronous AC-generator, and stall regulation. The Gedser Wind Turbine was operated for 11 years without any maintenance problems, and the tower, build in concrete, still stands, while other parts are kept at the Danish Museum for Electricity Physics, Technology, and Culture.

Juul was born in 1887, and having reached 70, the Gedser Wind Turbine was a crown jewel originating from a life dedicated to electricity production and wind power. In 1904, only 17 years old, Juul had gone to Askov Folk High School to attend a course for "wind-electricians" (Fig. 6) organised by Poul La Cour, an educated meteorologist, perhaps reasonably considered to be the founding father of Danish wind energy.

Already in 1897, La Cour had constructed wind turbines and a wind tunnel at Askov Folk High School, and began teaching about wind electricity. In 1904, he founded the Society for Wind Electricians and began publishing the Journal for Wind Electricity, the world's first journal on wind energy. La Cour's activities were timely. In 1918, 120 electricity companies had at least one wind turbine and wind power supplied 3% of the Danish electricity demand.

While wind energy did not come to play any greater role in-between the two world wars, the scarcity of fuels during WWII provided a motive for establishing a wind turbine combined with a diesel-generator to supply DC to the island of Bogø (Fig. 7).

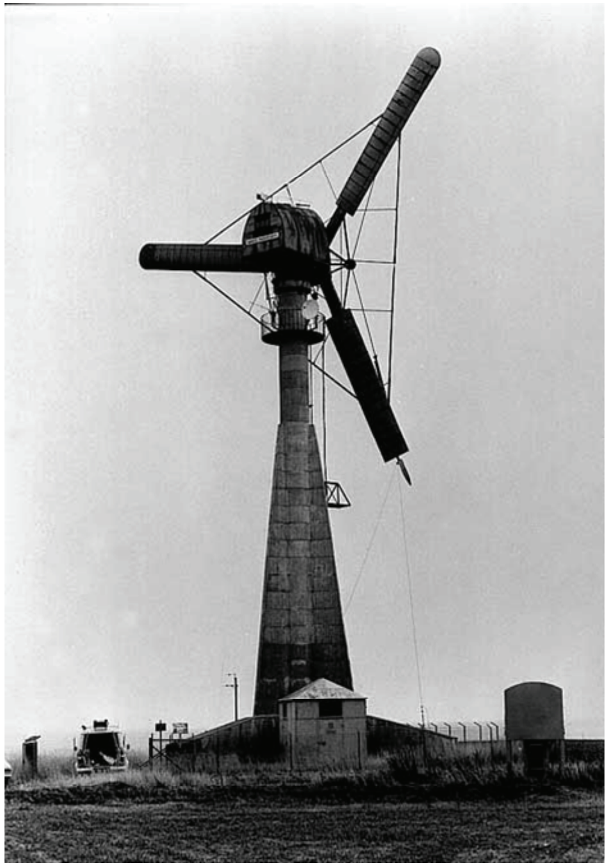

Fig. 5: The Gedser Wind Turbine.

Fig. 6: The 1904 class from Askov Folk High School (Copy of original picture printed with permission from the Danish Museum for Electricity Physics, Technology, and Culture).

Fig. 7: The Bogø Wind Turbine.

The aero-generator at Bogø was constructed in 1942 by FLSmidth, already a large industrial company at the time. While the tower may not have looked pretty, it was a solid cement product, and while the aero-generators were considered to be a side-product for FLSmidth, the production of numerous aero-generators during WWII helped getting the company through the war, while assisting FLSmidth in identifying their main competency: cement. Thereby the Bogø wind turbine supported FLSmidth in becoming today's world-wide leading producer of cement and cement industrial plants.

But the Bogø wind turbine also came to play a pivotal role in Danish wind energy research during the 1950s. From 1953 to 1960, Johannes Juul re-constructed and tested the Bogø wind turbine, and used his experience from this process to design and construct the Gedser wind turbine in 1957. Test results from Bogø and Gedser were presented at an international conference in 1961, and these experimental findings were in 1962 important to convince the Danish Wind Power Committee under the The Association of Danish Electricity Producers[8] that the principles and technology applied for the Gedser wind turbine were solid and reliable. And so it were; producing electricity reliably and effectively until 1967, two years before Juul's death in 1969. During the 60's, plentiful supply of low cost fossil fuels had made wind power look senseless, and interest in renewables were low and evading.

But then in October 1973, triggered by the conflict between Israel and neighbouring countries, OPEC agreed to increase crude oil price, which led to a world-wide economic chock. In one week, the price for crude oil tripled, and in one month, the happy 60's were forever gone, and were replaced by economic stagnation, car free Sundays, and laws against electric light in shop windows outside opening hours. Priests were exempted from car free Sundays (Fig. 8), but what should a wise man do?

The Danish society was facing a paradigmatic challenge; not only was transportation almost completely dependent upon oil, 85% of the electricity supply was oil-based. Up until the oil price crisis, oil-fired boilers and generators were cheap and

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[8] Now the Danish Energy Association (Dansk Energi).

straightforward technology. The period 1974-75 is, in retrospect, a most exciting moment in time, fuelled by uncertainty and a growing consciousness about the need to protect fundamental values. While oil restrictions are lifted in July 1974, a new price level had been established, and conflicting reactions were smouldering under the new effort to gain firm political control of energy; the Danish government initiated a law making process and the establishment of an institutional apparatus, leading to the Danish Energy Agency[9] in April 1976, and to the first national energy plan: "Danish Energy Plan 1976"[10] published in May 1976. The energy plan focuses on energy conservation, and on options for replacing oil in electricity generation, first with coal, then with nuclear power. Wind energy, and other renewables, "will not be able to contribute in any measurable extent on this side of year 2000", the Ministry of Commerce wrote. The energy plan reflects 2 years of official deliberations and exposes by the way the plan avoid taking conflicting interests into consideration, that in 1976, a critical level of polarization had been reached.

In reality, since early 1974, an outspoken struggle for values and technology had been taking place between a technocratic apparatus of supply companies and civil servants on one side, and an alternative-oriented civil society on the other. On January 4th, 1974, the board of the dominant electricity supply association Elsam presented the first plans for the introduction of nuclear power in Denmark. It had taken three months for the technocrats to find a solution to the oil price crisis; the answer was nuclear power. It took 3 weeks for the civil society to establish a counter-offensive, on January 31st, an association dedicated to supply Knowledge About Nuclear Power (OOA)[11] was established (Fig. 9).

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[9] Now Danish Energy Authority
[10] In Danish: Dansk Energiplan 1976
[11] In Danish: Forening til Oplysning Om Atomkraft (OOA)

Fig. 8: Permission to drive private vehicles on Sundays during the first oil-crisis awarded to priests.

Fig. 9: The famous OOA trademark "Nuclear - No Thank You".

OOA's first act was to demand for any political decision about nuclear power to be put off for at least 3 years. The establishment of OOA triggered both management and individual researchers at the Risoe National Laboratory wholeheartedly to voice their support for plans to introduce nuclear power in Denmark. In 1975, the continued active engagement of Risoe to promote the idea of nuclear power even led the social-democratic Danish government under Prime Minister Anker Jørgensen to ask Risoe to refrain from policy making, however at the same time declaring that "nuclear power is both necessary and essential to our supply situation"[12].

So it can be no surprise that the plans for introducing nuclear power were taking shape, slowly, but surely. In 1975, Elsam came up with a number of projections, which made it evident that nuclear power was the only feasible alternative to oil in electricity generation. The projections made forecasts for electricity demand based on economic growth projections, and were not really scenarios - supply and conservation alternatives were completely excluded from consideration.

Elsam's workings did not reflect the growing and increasingly active civil involvement in matters of energy and the environment. The summer of 1975 had been unusually hot, and a civil society association concerned with the environment, NOAH[13] had held its traditional annual summer camp on Avernakø, and for the first time providing a structured theme for discussion and experiments: nuclear power and renewables. Individuals returning from the camp realized that the opposition to nuclear power needed to be supplemented by an effort to promote alternatives, and on the basis of OOA, the Danish Organisation for Renewable Energy (OVE)[14] was established. Also in 1975, the construction of Barsebæk[15] began 20 km east of Copenhagen. The prospect of having a nuclear power plant added to the skyline takes Copenhageners to the streets

[12] Own translantion. In Danish: "kernekraftanvendelse er nødvendig og væsentlig for vores forsyningssituation."
[13] Now "Friends of the Earth Denmark". Established already in 1969 as a debate forum scheduled for Wednesday evenings on the Univeristy of Copenhagen (in Danish: Naturvidenskablige OnsdagsAftener (NOA)). Later, an H was added to represent the biblical character NOAH, supposedly the first environmentalist.
[14] In Danish: Organisation for Vedvarende Energi (OVE).
[15] Swedish nuclear power plant

on several occasions and in great numbers. An enemy to some had entered through the backyard, and the moment was tense and full of aggressions. And though the decision-makers were increasingly hesitant, the overall plan remained and was to prepare for the introduction of nuclear power.

There was just this really big problem: electricity companies were very effective in replacing oil with coal.

This success is evident in the national energy statistics, showing that coal's share of primary energy consumption in electricity generation had increased to 47% in 1976, up from 22% in 1972, a figure that would continue to increase over the decade, reaching 82% in 1980 (Fig. 10). It is likely that it was the successful transition from oil to coal that made it possible in 1976 to reach a broad consensus on postponing the decision on nuclear power. The decision led to the establishment of a national energy research programme, under which Risoe was commissioned to acquire knowledge about how to handle the radioactive waste, and at the same time to initiate research in alternative energy sources. In the first Danish energy plan in 1976, these were major instruments, but as the energy plan spelled out: still, the future is nuclear, making the transition to coal only a temporary step towards the introduction of nuclear energy.

The nuclear option remained to be valid, because the transition took place without changing anything fundamental in the design and overall functionality of the Danish energy system. The energy system was operated like before, only with a different fuel. And every projection showed that electricity demand was growing exponentially supposedly supporting the continued centralization of supply organisation and planning (Fig. 11).

But then, in 1979, as the transition from oil to coal in electricity generation is almost complete, the decision about whether or not to introduce nuclear power in Denmark is influenced by three particular events.

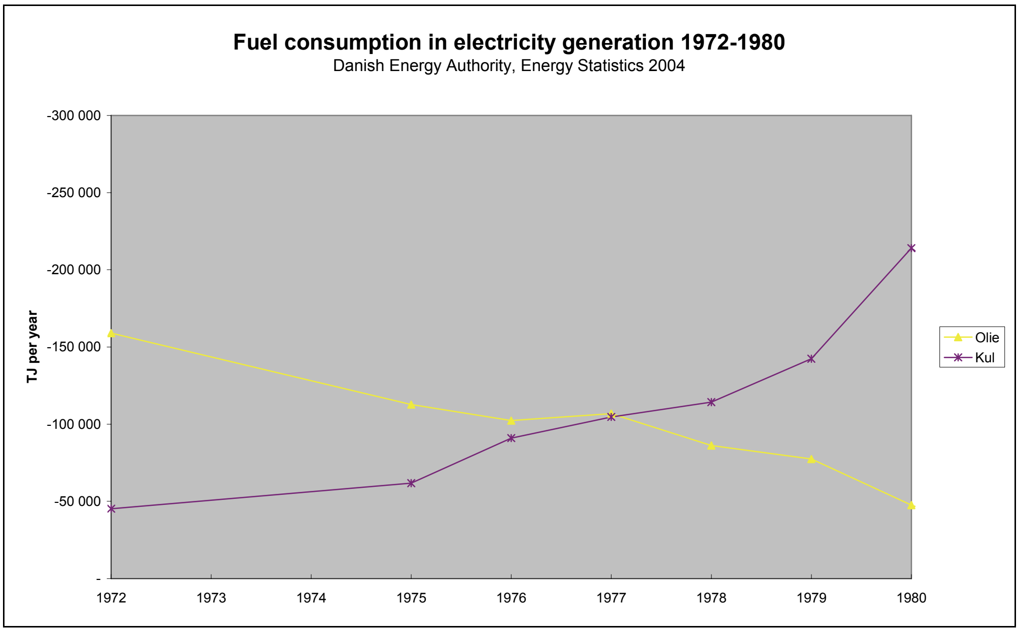

Fig. 10: Coal's and oil's share in electricity generation.

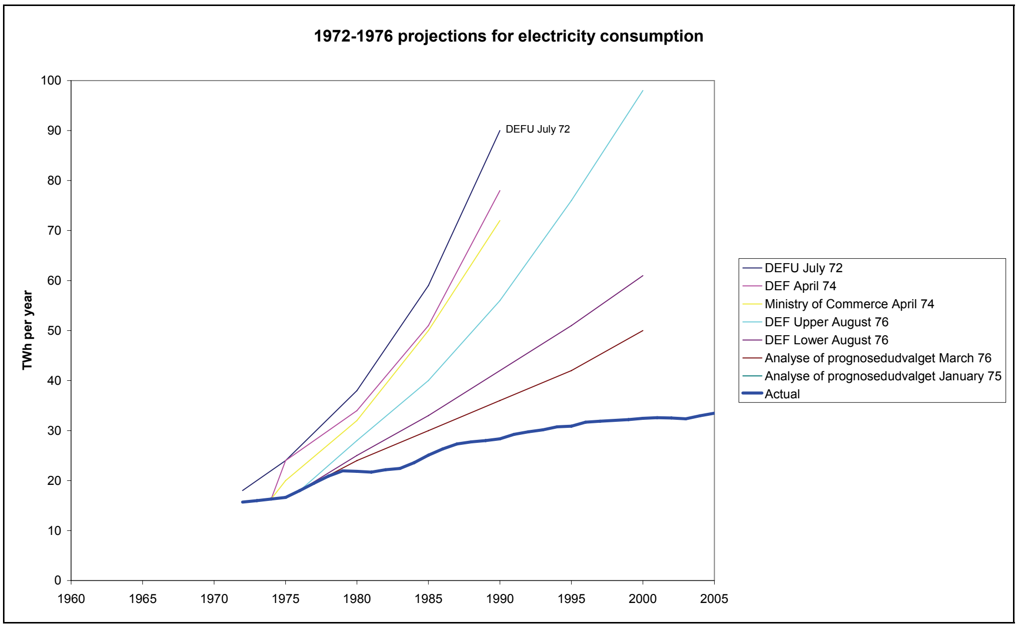

Fig. 11: Projection for electricity demand made in 1972-1976.

First, the war between Iran-Iraq brakes out and the world faces a second oil price crisis. Again the oil price tripled, and though Denmark's dependency on imported oil had been reduced to 76%, down from 92% in 1973, mainly due to the fuel-shift taking place in electricity generation, it was a serious blow to the economy, and something which led policy-makers to focus on oil consumption in individual space heating and transportation.

Secondly, a partial meltdown for reactor 2 at the Three mile-Island nuclear power plant in Pennsylvania, USA, becomes the world's first really serious nuclear power accident. The accident does not immediately halt efforts to introduce nuclear power in Denmark, but it leads to the commissioning of additional research on waste and safety issues. And thereby indirectly to the paradigmatic event in 1981, where Danish electricity company associations, Elsam in East and Elkraft in West, agrees to nominate the salt pits on the island of Mors for storing nuclear waste from future Danish nuclear power plants. No, says the Geological Survey of Denmark and Greenland, the salt pits are not safe. Elsam/Elkraft's openness and concrete geography and the subsequent qualified counter-analysis of uncertainty and risk are turning points for public opinion. From 1979 to 1984 the public opposition against nuclear power increased from 49% to 67%.[16]

Thirdly, in 1984, Maersk began supplying natural gas from the North Sea to the mainland, an effort that had been underway for a while. Despite indications, no one had at that time imagined the future scale of this domestic oil and gas production and supply.

"Clear nuclear power of the table"[17], OOA demanded in the autumn of 1984, and on March 29th, 1985, a majority in the Danish Parliament, consisting of the Social Democrats, the Social-Liberal Party, the Socialist People's Party, and the Left Socialist Party voted in favour of removing nuclear power as

[16] While I have no information about the share of interviees being in direct support of nuclear power in this survey, in June 2006 survey produced for Monday Morning Weekly, 69% of Danes are opposed to the introduciton of nuclear power in Denmark, which is close to the figure in 1984. In the 2006-survey, 15% are directly in support of introducing nuclear energy.
[17] Own translation. In Danish: ”Tag atomkraften af bordet”.

an option in public energy planning. From the legislation text, we read that the Mors salt pit concerns are raised, and that uncertainty is a key issue (Fig. 13).

The year after, during a research experiment starting in the late evening of April the 25th 1986, the Chernobyl nuclear accident happened. Today, 20 years after, a 100 km radius zone around the power plant is declared inhabitable, the meltdown is still in progress, and is expected to be so for 10,000 years. The principal effort to alleviate further impacts comes in the form a sarcophagus of iron and lead constructed up over and around the melting reactor.

Fig. 12: The Chernobyl sarcophagi as it appeared in March 2006.

The battle in Denmark against nuclear power continued as the battle against Barsebæk, which the Swedish government also committed to in 1998. The first reactor was shut down in 1999, as a result of which OOA, on May 31st 2000, dissolved itself, victorious having no unaccomplished objectives. The other reactor should have been shut down in 2001, but the disengagement was delayed until 2005. On the five-year anniversary day for OOAs dissolution, on May 31st at 6 p.m., Barsebæk was finally and irreversibly disengaged.

Fremsat den 12. februar 1985 af Lone Dybkjær (RV), Jytte Hilden (S), Margrete Auken (SF) og Tinning (VS)

Forslag til folketingsbeslutning

om offentlig energiplanlægning uden atomkraft

Folketinget pålægger regeringen at tilrettelægge den offentlige energiplanlægning ud fra den forudsætning, at atomkraft ikke vil blive anvendt.

Bemærkninger til forslaget

Udredningsarbejdet vedrørende atomkraftens sikkerhed, økonomi og affaldsopbevaring er nu afsluttet, jfr. miljøministeriets rapporter af februar og marts 1984 om sikkerheden ved kernekraftværker, placering af kernekraftværker og vurdering af elværkernes salthorstundersøgelser samt energiministeriets rapport af november 1984 om forhold af betydning for elektricitetsproduktion på basis af kul og uran.

På denne baggrund er det forslagsstillernes opfattelse, at atomkraft med den viden og teknologi, der er til rådighed i dag, skal udgå af den danske energiplanlægning, hvorfor det pålægges regeringen at drage de nødvendige konsekvenser heraf.

Forslagsstillerne opfordrer energiministeren til straks ved begyndelsen af folketingsåret 1985-86 at give det energipolitiske udvalg en redegørelse for iværksatte og påtænkte foranstaltninger til efterlevelse af beslutningsforslaget.

Folketingsbeslutningen blev vedtaget ved 2. (sidste) behandlingen den 29. marts 1985, med 79 stemmer (S, SF, RV og VS), mod 67 (KF, V, CD, KrF og FP).

Fig. 13: In 1985, Parliament excludes nuclear energy from energy planning.

Fig. 14: The Riisager Wind Turbine.

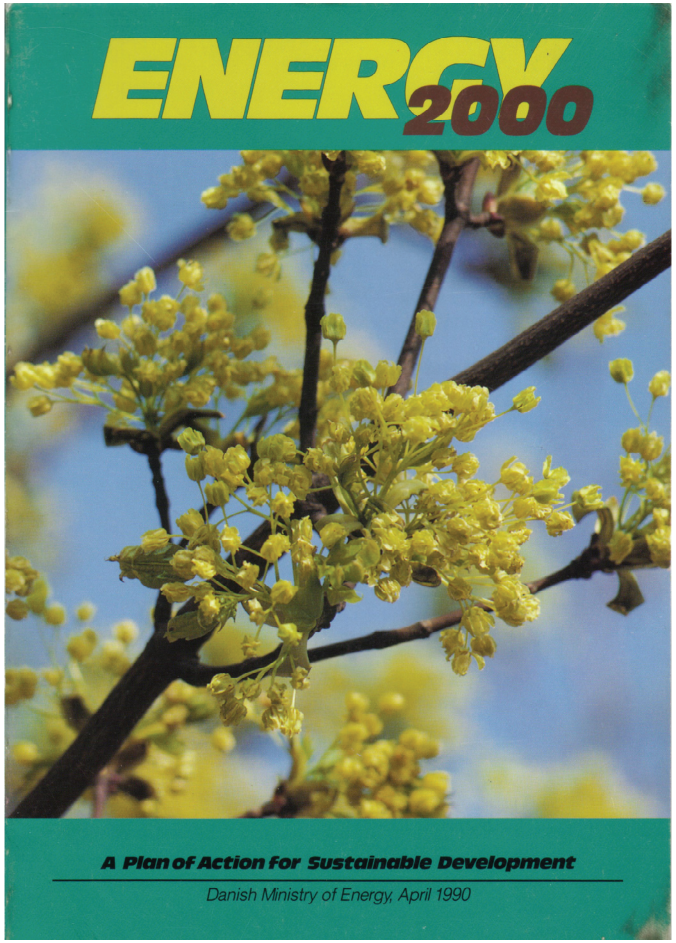

Fig. 15: Energy 2000: The World’s first official national sustainable energy plan.

With effective steps for removing nuclear energy as an option in energy planning in 1985, how had the alternatives fared?

Inspired by the basic principles of the Gedser wind turbine, Christian Riisager's carpenter workshop in Lind, near Herning, from 1976 to 1980 build 72 Riisager wind turbines, which was the commercial and manufacturing breakthrough for the cheap, series produced, and grid-connected wind turbine (Fig. 14). The turbines were price-tagged just under DKK 50,000, producing more than 30,000 kWh per year, equivalent to the electricity demand in 10-15 average households. The wind turbine was robust, and effective, and the Riisager wind turbine became known country-wide, when the very first wind turbine was sold to a journalist at Information, Torgny Møller. The life of the wind turbine ended up as daily news in Information, and the Riisager wind turbine established wind power as a reliable alternative.

But it took a while for wind power to find mentioning in any official energy policy. In "Danish Energy Policy 1976" it was not mentioned by a single word. It was however a major element in the first so-called alternative energy plan from October 1976, "Draft Alternative Energy Plan for Denmark", which was independently prepared, however financed by OOA and OVE in collaboration [21]. The plan had 8 authors within various areas of expertise in the energy field, including Professor Frede Hvelplund and Professor Niels I. Meyer. The alternative plan introduces an important energy planning principle that should come to influence future energy planning efforts: the principle of leading a qualified techno-economic debate on alternatives, here focusing on relative benefits in terms of economics and primary energy consumption. With the "qualified evaluative" principle, it is established that researchers and independent experts working on alternative options would come to have an important role in influencing the basis for decision-making, and that technology developments in society may be effectively influenced when evaluated on a reasonable basis.

It is not until Denmark 3rd official energy plan, "Energy 2000 – a plan of action for sustainable development" [22] (Fig. 15), published in the spring of 1990, that renewable energy and energy efficiency got a central position in energy planning. Energy 2000 illustrates a political shift that began with notions of globalisation as a condition, and with the publication of "Our Common Future" in 1987. It was not at least the personal dedication of the Minister of Energy, the social-liberal party's first-mover on sustainable energy, Jens Bilgrav-Nielsen, that led to Energy 2000, thereby indicating that political intend and forcefulness is an influential factor in bringing about change. With Energy 2000, it becomes evident that making an energy plan and introducing instruments to support it would be required to turn things around. The human-created greenhouse effect is put on the agenda, and despite wide-spread doubts and scepticism, for the first time in any national energy planning, an environmental target is introduced as a tangible indicator for the success of the plan. A key element in the plan is the objective to reduce CO2-emissions from the energy sector by 20% in 2005, relative to the level in 1988. The specific target was carbon-copied from the international climate conference in Toronto in 1988 that recommends a global reduction of 20% for 2005.

A critical mass of events, a timeline for which is illustrated in Fig. 16 had been reached for a unique energy system by global comparison with high exergetic efficiency and the second lowest carbon footprint among non-nuclear energy systems. And we understand that in order to make sense of the Danish experiment, we need a narrative that brings together various historic events such as Johannes Juul and his Gedser Wind Turbine with Grundtvig's Folk High Schools, the Israeli-Palestinian conflict, alternative-oriented island camps on Avernakø in the 70's, the public Danish opposition against a Swedish nuclear power plant, and Energy 2000.

The decision in 1985 to remove the nuclear option from energy planning was a turning point that provided a constitution for the future of the Danish energy system. The decision came at a time where conflicting social models battled for Denmark's affiliation; was the socially-oriented country to associate with South, North, East or West for answers, to a Nordic Community, Russia, EU, or USA? When this important issue of conflict was settled, nuclear power or not, it provided the opportunity for Denmark to focus on self-sufficiency, on local resources and supply options, and perhaps even the decentralization of the political world view that came to strengthen our affiliation with EU.

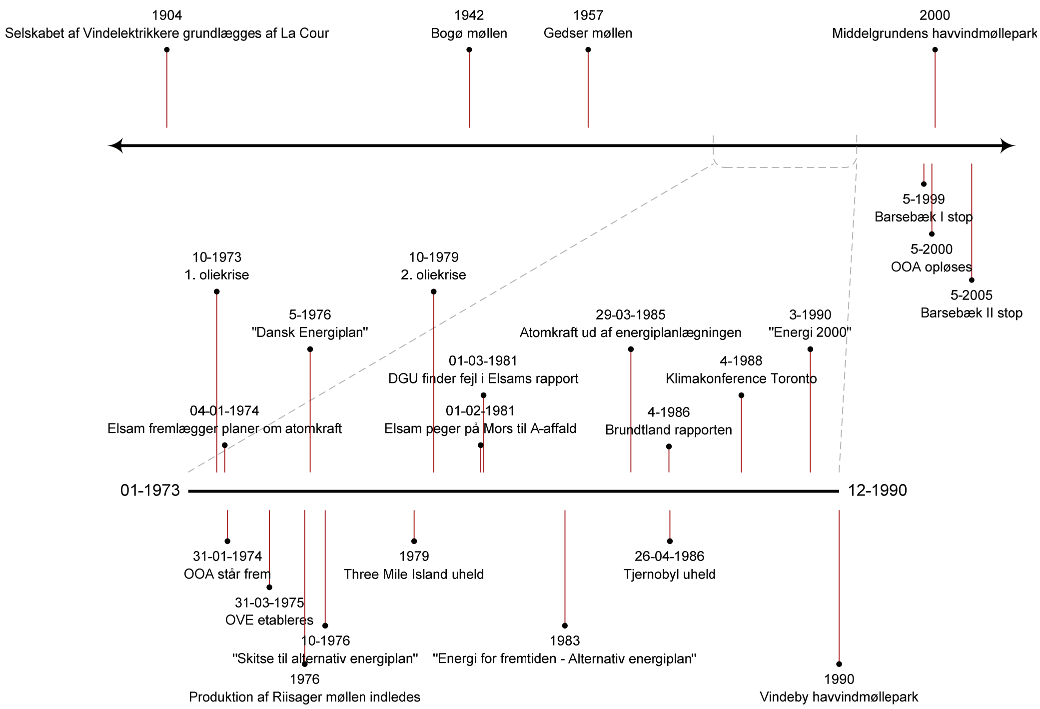

Fig. 16: Critical events in the evolution of the Danish energy system.

In reflection, 1985 happened at a time where the institutionalization process in the energy sector was young, yet the decision gives evidence to how far Denmark already had gone in terms of institutionalizing energy, with a Ministry of Energy, Government controlled supply companies, energy and environmental legislation, price signals in the form of taxes and rates. But Denmark was not "locked in" by any unchangeable technological strategy, and this techno-institutional plasticity made the decision possible.

The effective removal of nuclear power from energy planning in 1985 was the starting point for Denmark to embark along a particular path of social and technological transition. In combination with other events, it is a decisive moment in the development of the Danish sustainable energy system, and a decision from which contemporary Danish policies originate; environmental and energy policies, economic policies, and geo-political policies.

But 1985 cannot be detached from the other events described, which bears witness to the hypothesis that this is really a story about a partnership effort between bold Government policy-makers that took a unilateral step of faith by a narrow majority, and a civil society open to non-conventional experiments.

In closing, let us return to consequences of this development with respect to CO2 emissions, fossil energy consumption, and the economy.

2.2 Energy, environmental and economic consequences

It is evident that a strong historic correlation exists between economic growth and primary energy consumption, and classical economics has continued to disregard energy as a production factor, in result of which the consumption of fossil energy resources is not regarded an input, a cost, but rather a production output. This brings understanding to the view of neoclassical economists that find that "[r]educing energy consumption for environmental reasons can never be a costless option unless by chance the action taken happens to coincide with the action necessary to achieve general economic optimisation." [23].

In neoclassical economics only capital and labour are production factors, while energy consumption has been considered an intermediate product of the economy. This is a fundamental flaw in neoclassical economics, at least according to Robert E. Ayres, the most recent economist to put forward the argument that exergy, the provision of energy services, significantly impacts economic growth [24]. While Nobel Prize Winner James Tobin and William Nordhaus found that economic growth correlates with Measured Economic Welfare, the MEW index, Ayres argues that economic theory and models should be revised to take into account exergy as a production factor. Doing so would have an impact on the welfare measures itself, and would provide an improved measure for showing when economic growth is un-economic. Does the disregard for exergy in classical economics allow one to suggest that economic growth theory has contributed to the ecological crisis? The Kuznets Curve shows how even uneconomic growth will eventually solve the environmental problems, but ecological economists, like Herman E. Daly, have argued that economic growth may be un-economic, and irreversibly so.

With Ayres, arguments are made for incorporating the notion of exergy into classical economics, and developments in Denmark's economic growth and primary energy consumption indicate that, if doing so, both neoclassical economists and ecological economists are now right. Energy is not a production factor, however exergy is, and economists have just been late to distinguish between the two.

Therefore it is a gross misunderstanding that "thanks to energy policy [...] it has been made possible to decouple economic growth and growth in energy consumption" [25], a point which gained particular international recognition and momentum after Prime Minister Anders Fogh Rasmussen made it his main point during his speech on the global climate summit in New York in September 2007. "It is indeed possible to pursue economic growth – while at the same time stabilizing consumption of energy and safeguarding the environment [...]. Our experience in Denmark shows that we can maintain economic growth and reduce the dependency on fossil fuels. Since 1980 Denmark's economy has grown by approximately 70% - with a nearly unchanged consumption of energy", Rasmussen said in his speech [26]. "These numbers impressed everyone. 70-0 [to Denmark]", Andersen later said to Politiken [27]. Former president Bill Clinton was early to appreciate Denmark's experience, and at the U.S. Conference of Mayors Climate Protection Summit in November 2007, he offered Denmark as an example to follow as someone who has made "a serious commitment to an efficient, sustainable energy future". As Clinton recalls: "[Denmark] expanded their economy by 50 percent with zero increase in energy use" [28].

So besides being recognized for hosting the largest wind producer in the world, Denmark is increasingly known for being the first Western country to decouple economic growth and growth in primary energy consumption. The problem is that it is not correct.

Firstly, 1985 is probably a much better starting point than 1980 for understanding how social and techno-economic changes turned around the Danish energy system. This should become evident by the historical events described later in this chapter. And the fact is that between 1985 and 2006, the Danish economy increased by 40%, while primary energy consumption increased by 10%. It seems as if energy consumption is actually continuing to grow, even picking up speed since 2003, as also the economy continues to grow. However, the consumption of fossil fuels and energy sector CO2-emissions have decreased, by 5% and 12% respectively, but even for these elements, it seems as they are again turning around to positive growth rates for 2005 and 2006 (Fig. 17).

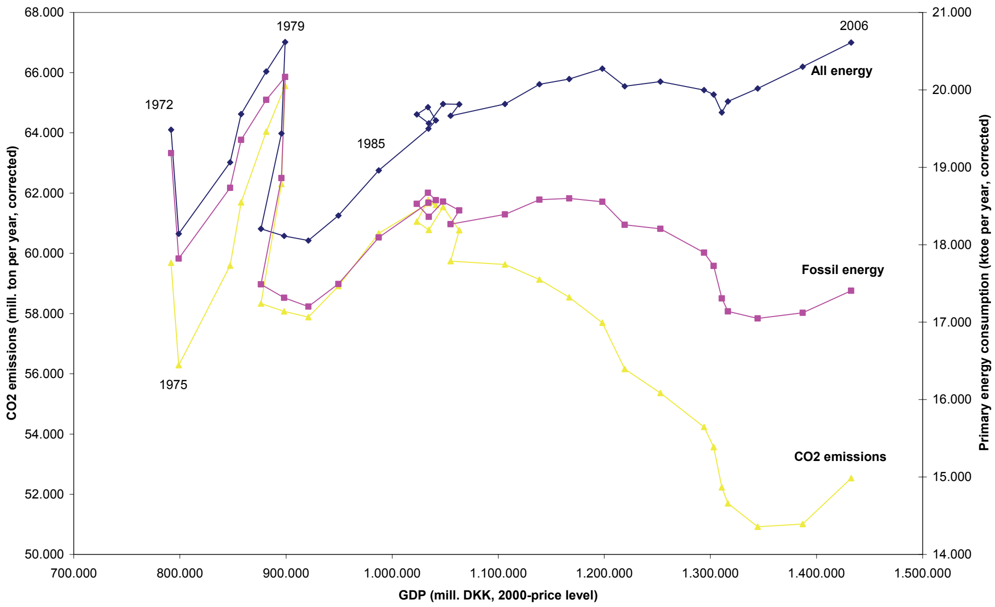

Fig. 17: Relationships between Denmark's economic growth, energy consumption, and CO2 emission from 1972 to 2006.

So, while international policy makers hails Denmark for proving that old neoclassical economic theory is right to assume that energy is not a production factor, apparently decoupling economic growth and growth in energy consumption, properly used statistics are actually indicating that they are wrong. Rather, Denmark is proving that ecological economic theory and new neoclassical economic theory is right to say that useful energy is indeed a production factor: primary energy consumption does really continue to grow as the economy grows, and only in a steady-state economy, this growth comes to a halt. What is happening is that fossil energy consumption and environmental impacts are eased, and that the economic benefits associated herewith are not fully appreciated in classical economics, quite in accordance with Ayres hypotheses [24].

The standing hypothesis is therefore that useful energy is indeed a production factor, and therefore, serving an economic purpose in its own right, there is *per se* economic reason for increasing the exergetic efficiency of the energy system. Despite such *per se* reasoning, we may also get an indication of the economic value of increasing the Danish energy system's exergetic efficiency between 1985 and 2006, by applying late 2007 world spot market prices for oil, gas, and coal to the fossil energy resources that was not used in the period. It is probably fair to assume that efforts to reduce fossil fuel consumption are likely to have influenced GDP growth negatively, due to the investments made when replacing fossil fuel consumption, even when accounting for saved annual operational costs. If assuming so, and simply adding the current value of saved fossil fuels to GDP, we find that the Danish economy has not grown by 2,4% per year, but by 5,6 per year, since 1985.

In other words, Denmark has not decoupled energy and economy, rather 20-year statistics suggests that the time has indeed come for neoclassical economic theory to make a distinction between energy and exergy. But from the Danish experiment we learn that fossil energy consumption, and environmental impacts may be decoupled from economic growth, something which is accomplished by increasing the exergetic efficiency of the energy system. In accordance with ecological economic theory, only in a steady-state economy, the growth in the consumption of useful energy, or exergy, may be effectively stopped.

The Danish energy experiment indicates that energy and environmental policies in support of solving the climate crisis should focus on exergy, but do they?

3. Defining sustainable energy

The meaning of the term [sustainability] is strongly dependent on the context in which it is applied and on whether its use is based on a social, economic, or ecological perspective, Sustainability may be defined broadly or narrowly, but a useful definition must specify explicitly the context as well as the temporal and spatial scales being considered. Brown, 1987 [29].

In defining sustainability, the Brundtland Report [30] emphasizes the importance of protecting the natural environment, and sustainable energy is most often considered to be a prerequisite for a sustainable environment. But the Brundtland Report does not define sustainable energy; rather it is fair to say that by defining only sustainability, the Brundtland sees sustainable energy as *the energy component of sustainable development*.

In one of the first comprehensive books that deals with energy from a sustainability perspective, Goldenberg et. al. [31] tries to understand "how patterns of energy use might be shaped so as to promote the achievement of certain basic societal goals – equity, economic efficiency, environmental soundness, long-term viability, self-reliance, and peace", thereby attempting to define sustainable energy.

However, these original definitions are overshadowed by the widespread praxis to consider sustainable energy simply as building on two pillars: renewable energy and energy conservation. In result, the two-pillar theory of sustainable energy is often practised as the idea that if fossil fuels are replaced by renewables and energy is conserved, then the energy system will be sustainable. The two-pillar theory is easily challenged, and in this chapter, I will provide evidence to falsify it, and suggest an original definition and theory for what sustainable energy is.

3.1 Conventional sustainable energy policy theory

In the monumental research produced as a result from "The Danish Democracy and Power Study"[18], Professor Kurt Klaudi Klausen and Professor Torben Beck Jørgensen describes Denmark's political and administrative structure as a dual-structure: "From the top, there is the state, which from the central administration at the Slotsholmen branches out in to the country – the National Denmark – gradually to be replaced by the municipal structure, that grows from beneath, having its apex with Danish Regions[19] and Local Government Denmark[20] in Copenhagen – the Municipal Denmark" [32]. However, this dual-structure is being challenged, also the professors conclude, on the basis of various case studies.

One key challenge arrives from EU common policies. EU was founded on the basis of energy related concerns. The European Coal and Steel Community established in 1951, and the European Atomic Energy Community established in 1957 kicked off what was to become the European Community.

But it was not until March 9, 2007 that the Council of Ministers voted to agree upon a common energy action plan [33]. While it is not called a policy, the Commission's energy package "An energy policy for Europe" that precedes the agreement leaves little doubt that this is indeed EU's first energy policy [34]. The action plan hold four major elements: the internal market for energy, security of supply, mainly of gas and oil, and greenhouse gas emissions, a common international energy policy, focusing on supply agreement with Russia, Africa, and Asia, as well as energy efficiency and renewables.

For energy efficiency, a tangible target of 20% is set for 2020 following the Commission's Action Plan for Energy Efficiency (2007-2012) published in 2006 [35].

For renewables, the target reads 20% for 2020 similarly adopting the Commission's Renewable Energy Road Map published in 2007 [36]. The Council furthermore reconfirms

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[18] In Danish: Magtudredningen.
[19] In Danish: Amtsrådsforeningen, now Danske Regioner.
[20] In Danish: Kommunernes Landsforening.

EU's commitment to reducing CO2 emissions by 30% in 2020, compared to 1990.

With respect to energy and environmental policies in support of solving the climate crisis, EU is proposing a policy for sustainable energy that builds on two pillars: renewables and energy efficiency.

The Danish "Energy Policy Agreement of February 21, 2008" is establishing a similar two-pillar approach to the problem, proposing specific technology targets for energy efficiency and renewables. The objective here is to reach 20% renewables in energy supply by 2011, and 30% by 2025, up from 16% in 2007. These targets are in line with Denmark's EU energy policy commitment to reach 27% by 2020. Among the technology targets is the plan to increase the installed wind power capacity by 150 MW on-shore and 400 MW off-shore. Another target exists for biofuels to represent 5,75% of total fuels in transportation by 2010.

Are EU's and Denmark's efforts evidence of sustainable energy policies? Or could it be that the two-pillar praxis to allow for energy efficiency and renewables to define sustainable energy results in flawed interventions that are counter-productive?

3.2 Falsifying the two-pillar theory

The two-pillar theory is open to falsification, and attempts to falsify it, identifying black swans [37], are easily prepared.

For example, while biomass is a renewable energy resource, there is evidence that replacing fossil fuels with biofuels may pose serious social, environmental, and economic risks. In April 2007, atmospheric scientist professor Mark Z. Jacobson of Stanford University found that ethanol vehicles, independent of the origin of the ethanol, while reducing atmospheric emissions of benzene and butadiene, increases emissions of formaldehyde and acetaldehyde, all of which are carcinogens, and while his first conclusion is that cancer related deaths are likely to be similar for gasoline and ethanol fuelled vehicles, he also found that ethanol fuelled vehicles increases ozone emissions, and that replacing 15% of gasoline with ethanol would be likely to lead to an increase of about 4% in ozone-related deaths in 2020 [38]. In another study prepared by researchers at Universitat Autonoma de Barcelona it is indicated that CO2 reductions for biofuels may be negligible or even negative, mainly due to the way biofuel is being produced. In yet another study, Nobel Prize winner Poul Crutzens finds that the production of biodiesel from rapeseed and bioethanol from corn due to N2O emissions can contribute as much or more to global warming as fossil fuels [39]. It only adds to the problem that the production of biofuels is becoming responsible for much of the deforestation taking place in South East Asia and in Brazil. In Malaysia, between 1985 and 2000 palm oil plantations caused 87% of the total deforestation, deforestations rates remain high at 3,9% p.a. for 2000-2005, and existing plans for deforesting will make room for further 6 million hectares of palm trees, equivalent to another 16% of Malaysia's share of Borneo [40]. Similar efforts are underway on the Indonesian side, which has expanded palm oil plantations from 600,000 hectares in 1985 to 6 million today, with plans for reaching 10 million hectares by 2010 [41].

I would like to contribute with an eye-witness account of my own, having worked in Malaysia from 2000 to 2005, at a couple of occasions flying over what I initially thought was rainforest, because it was mapped as such. Today, seeing only endless fields of palm oil trees, I was left with the impression that logging of rain forests and subsequent palm oil plantations on Malaysian Borneo, increasingly targeting a market supported by European biofuel demand, is a mistake that will hurt future generations, while rewarding only short-term interests. From this perspective, the idea of introducing biofuels, a renewable energy resource by technical definition, to replace fossil fuels appear to hold serious risks towards a sustainable development.

For large-scale hydro power, another renewable energy resource by technical definition with concerning impacts, recent studies postulate that due to an abrupt reduction in the river flow caused by the Yangtze River Three Gorges Dam, the world's largest hydroelectric construction, the East China Sea is experiencing significant changes in microbial diversity, including the loss of pico-plankton, the result of which is likely to have a noticeable effect on the marine life [42]. In another study, researchers from the University of Brasilia and the Federal University of Rio de Janeiro published an article in

Energy Policy to document that large-scale dams under Brazil's so-called sustainable energy policies are in fact "harming rich Amazon wetland ecosystems" [43].

"Renewable energy is not green" claims Jesse Ausubel, director and senior research associate of the Rockefeller University, in the International Journal of Nuclear Governance, Economy and Ecology, based on his assessment of the land-use required if hydro, biomass, wind, and solar renewables alone were to provide for today's energy demand. For example, Jesse Ausubel finds that one km^2 of dammed land is required to provide electricity for every 12 Canadians, and that every vehicle in the US would require 1,5 hectares for biofuel crops, and that "considered in watts per square metre, nuclear has astronomical advantages over its competitors" [44]. While the analysis seems to be made in an effort to promote nuclear power as a climate friendly energy resource and technology, the problem of extensive land-use associated with certain renewables is evident, and has been investigated for Denmark and EU by Dr. Kaj Jørgensen from Risø National Laboratories, who finds that biomass availability is limited mainly as a physical resource, rather than by environmental and economic consequences, while quoting findings from the European Agency for the Environment that the technical potential for environmentally acceptable biomass crops for energy purposes in EU-25 represent only 12% of total primary energy supply in 2006 [45].

While more examples of potentially non-sustainable impacts of renewables may be provided, it should be evident that building a theory of sustainable energy simply upon the pillar of renewable energy sources is failing.

But at least energy conservation, the second pillar, always induces positive environmental consequences towards sustainability, right? Well, not always. For Denmark, it may be argued that efforts to reduce residential space heating demand within district heating networks risks undermining future investments in distributed co-generation. As continued investments is necessary to maintain an energy system based on distributed cogeneration, the discontinuation of investments could mean the return to the split supply of heat and power, which could turn into a less resource efficient energy system. It is therefore evident that even demand side changes are required to be put into perspective of how it impacts context, in this case the entire energy system, and that even energy conservation is no solid pillar in defining sustainable energy.

I have come to think that renewable energy and energy conservation fails to describe what sustainable energy is. So what would be a better theory of sustainable energy?

As it is, claiming a more efficient land-use than renewables, Ausubel considers nuclear power to be sustainable energy and an appropriate response to the climate crisis. A typical argument against considering nuclear energy as sustainable energy refers to the two-pillar theory, in saying that nuclear power is not sustainable energy because uranium is a depletable resource. Other arguments quickly follow, referring to all the other problems associated with nuclear energy, mainly waste disposal, operational safety concerns, nuclear proliferation, and social organisation. However, the current two-pillar theory does not allow references to these other problems as they are not referred to in the definition. The only valid argument relying on the two-pillar definition is that uranium is not a renewable energy source.

But even for this argument, nuclear science seems to have an answer. While uranium may be expected to be available for perhaps as long as 350 years at the current rate of consumption, when used in light-water reactors, the introduction of new reactor types, particular referring to the promises of the fast breeder reactor, the uranium resource may last 10,000 years, in praxis establishing itself as a lasting resource [46]. In his Ph.D. thesis, Wilfred van Rooijen from the Delft University of Technology shows how this is possible with the Gas-cooled Fast Reactor concept that produces virtually no long-lasting nuclear waste, acting as an incinerator of nuclear waste in a closed fuel cycle [47].

A similar cycle of arguments are carried out with respect to coal and so-called clean coal technologies, which are, by some, confidently categorized as sustainable energy. Proponents will argue that resources are lasting and that the problem of storing emissions is manageable [48].

Professor Noam Lior of University of Pennsylvania, the dedicated editor of Energy – The International Journal, suggests in a recent review retreating to the original definition according to Brundtland, by saying that "while having various definitions, we can simply state here that sustainable activities mean that they meet the current needs without destroying the ability of future generations to meet theirs, with a balance among economic, social, and environmental needs" [49].

But "... without destroying the ability of future generations" is that not necessarily a criteria in itself, more important than anything else? And it is not so that an unsolved climate crisis would destroy civilization?

3.3 A better sustainable energy theory

Acknowledging the climate crisis, I find that it is time to take the notion of a crisis situation seriously to the extent of turning to crisis management and some reductionism with respect to secondary goals and means. In this respect, I see a fruitful perspective for no longer arguing against a perceived reality that considers for sustainable energy to be energy sector responses to the climate crisis.

By this proposed definition, sustainable energy is climate crisis solutions.

This will fundamentally teach us not necessarily by default to favour a solution because it is so-called sustainable, as we will openly and constructively come to appreciate the existence of more than one candidate solution to the climate crisis. Sustainable energy requires a careful assessment of consequences in context – and is not *good* by default.

The point here is that the pillars of renewable energy and energy conservation are means to an end, not the end itself, and that these pillars are incapable of capturing the essence of sustainable energy. What's needed are effective responses to the climate crisis which requires for definitions that allows for means to be considered on equal terms, but most importantly for sustainable energy science to acknowledge that the rationalities juxtaposed serves particular economic and political interests.

By the proposed definition, also nuclear energy is a sustainable energy option, and should be evaluated on equal terms with other proposed climate crisis solutions. With respect to

CO2-neutrality, from a life-cycle perspective, most will agree that nuclear energy is an option for reducing GHG-emissions from the energy sector. For example, in one study assessing the GHG-emissions from a life-cycle analysis approach for photo-voltaics and nuclear power, researchers from Brookhaven National Laboratory and Columbia University have found that GHG emissions in a US context are almost similar for photo-voltaics and nuclear power at 22–49 g and 16–55 g CO2-eq. per kWh-electricity respectively [50]. From an operational fuel use approach, it is obvious that the GHG-emission reduction potential is substantial when replacing fossil fuels with nuclear and renewables, for example for coal and gas for which GHG emissions could average 950 g and 405 g CO2-eq. per kWh-electricity respectively. Other studies suggest that nuclear energy from a life-cycle or fuel-cycle perspective is comparable to photo-voltaics.

But is nuclear energy then a wise response to the climate crisis? This is the relevant question.

Nobel Price laureate Al Gore thinks not. He argues that nuclear energy should not play a significant role in the future as a new source of electricity due to the economic costs and the risk of nuclear weapons proliferation [51]. But Al Gore is not opposed to nuclear power, and he is not questioning those 439 commercial nuclear power reactors under operation in 30 countries today, facing a that spells that while policy plans for abandoning existing nuclear energy programs are in the works in Sweden and Germany, 56 countries operate civil research reactors, in several of which full-scale programmes are eminent [52].

It should fairly be added that Gore's concerns about economic costs and about the risk of adding to the list countries known to have nuclear weapons: Russia, USA, UK, France, China, India, Pakistan, and Israel, with certainty, and with Iran and North Korea as potential short-term candidates under scrutiny, some nuclear scientists claim that new reactor types are less costly, passively safe (only sensitive to mal-attacks), and proliferation-resistant [46].

With the new definition of sustainable energy suggested here, sustainable energy science will no longer have to feel like Sisyphus trying to argue why nuclear energy is not a sustainable energy option, but move on to investigate nuclear energy and other sustainable energy options with respect to rationality and power.

3.4 Territories of power

"In the coming century, there are [...] two main options for Denmark's energy supply: nuclear energy or solar energy (including wind, wave, etc.)" Bleggaard et. al. [21] wrote in the concluding chapter of the first alternative energy plan in 1976, perhaps the world's first techno-economic consistent and qualified alternative energy plan. This is perhaps really a defining choice that needs to be made in energy system design: the choice between possibly incompatible options, between nuclear energy and intermittent resources? But is it true that nuclear energy and intermittent resources really are incompatible? And if so, in which way are they incompatible? And what consequences should this have with respect to the way we attempt to evaluate and compare options in energy?

Nuclear and wind are *techno-economic* incompatible, according to previous manager in the West Danish system operator Eltra, and an expert in the Danish electricity system, Paul-Frederik Bach. "The system cannot be designed for both options to co-exist without serious economic consequences," he says. His conclusion is that nuclear energy is incompatible with the current Danish energy system, which is based on wind power and distributed generation. Bach's conclusion is supported by professor Dr. Poul Lebeck Ølgaard from Risoe National Laboratories, an expert on nuclear energy research, saying that "the electricity system would clearly have to undergo changes if nuclear power was introduced [...].Nuclear power plants operate continuously [...] and should be dimensioned as base load plants in the system. In result, nuclear power plants would compete with current base-load technologies, wind power and distributed generators. On a high note, Ølgaard continues to say, that "... at least, this would give us an energy system, which is easily controlled, because it is does not depend upon wind and weather conditions." [53]

Interestingly, only little research is found that considers a combination of nuclear energy and intermittent resources, and some of that may not be properly careful in considering the technical operational differences. One article published in

"Progress in Nuclear Energy" suggest that a potential synergy exists between wind power and nuclear energy when combining these technologies in the production of distributed hydrogen [54]. Another article published in "International Journal of Energy Technology and Policy" finds by dynamic programming that 20% nuclear energy, 5% wind power, and 8% cogeneration is the optimal mix for India's future energy system [55]. In "Solar Energy", researchers from University of Leuven in Belgium, published results from modelling GHG-emission consequences of introducing up to 1500 MW wind power in Belgium's energy system, in which nuclear power in 2004 made up 55% of total electricity production. The reduction potentials were found to be ranging from 350 to 450 kg CO2 per MWh of power generated by wind power, comparable to marginally displacing gas-fired power plants [56], however it should be realized that 1500 MW wind power would correspond to only about 4% of Belgium's total electricity production in 2004.

There is however substantial research that indirectly supports the understanding, that nuclear power and intermittent options are incompatible, for example by way of comparing the two options as alternatives to each other, i.e. *per se* incompatibles. In 2003, researchers from IAEA and Centre for Energy Research (NZ) published a study in "Energy Policy" that compares three basic resource options: fossil fuels, nuclear energy, and intermittent energy [57]. While concluding that only nuclear energy is a mature alternative to fossil fuels, the authors were considering the resources as competing platforms for energy system developments. In 2003, researchers from Eastern Mediterranean University and Bahcesehir University published an article in "Energy" with results from a study that compared a nuclear energy program with a cogeneration program for Turkey, concluding that the nuclear option would be USD 72,6 billion more costly in 2020, in terms of accumulated costs [58]. The article does not consider any combination of nuclear power and cogeneration.

National energy sector statistics indicate that nuclear energy and intermittent resources are incompatible options. Combining data from IEA and EUROSTAT, Fig. 18 illustrate the shares of cogeneration and intermittent production as a function of the nuclear share of total electricity production in 2004. A medium negative correlation of -0,27 between nuclear and intermittent production, and a weak negative correlation of -0,14 between nuclear and cogeneration may be carefully used to suggest that nuclear energy finds it difficult to co-exist with distributed cogeneration and intermittent resources. As this is not surprise - a growing share of one resource is certainly likely to reduce the share of another – it should be noticed that in energy systems for which the share of nuclear power has gone above 27% of total electricity production, no room is left for intermittent resources, with Sweden as an exception with 1% intermittent supply share. However, for less shares of nuclear power, we see no statistical evidence for incompatibility. The cases of Germany and Spain are particularly worth noticing. While the share of nuclear power reaches 27% and 23% respectively, the contribution from intermittent production is significant and increasing, currently at 4% and 6% respectively. In EU-25, these penetration rates are only surpassed by Denmark.

Fig. 19 addresses the potential compatibility between intermittent resources and cogeneration dividing European energy systems into two categories: nuclear and non-nuclear. For nuclear energy systems, there is a weak negative correlation of -0,14 between cogeneration and intermittent production, while for non-nuclear energy systems, there is a very strong positive correlation of 0,77. Nuclear energy systems do not only discourage the penetration of intermittent resources, but they do also discourage the combined penetration of cogeneration and intermittent resources. In contrast to this, we see that in non-nuclear energy systems, increasing shares of cogeneration supports increasing shares of intermittent resources. These conclusions are based on a single year aggregate statistical representation, and the correlation results are highly sensitive to the inclusion of the Danish energy system.

The existence of competing and conflicting models are evident in the October 2007 attempt by the European Commission to map the various capacities of the member states with respect to energy [59]. About one out of three Member States list nuclear-related research among the first priorities in the national plan (not surprisingly for countries exhibiting a relatively nuclear-intensive power sector, headed by France, and followed by Lithuania, Bulgaria and the Czech Republic).

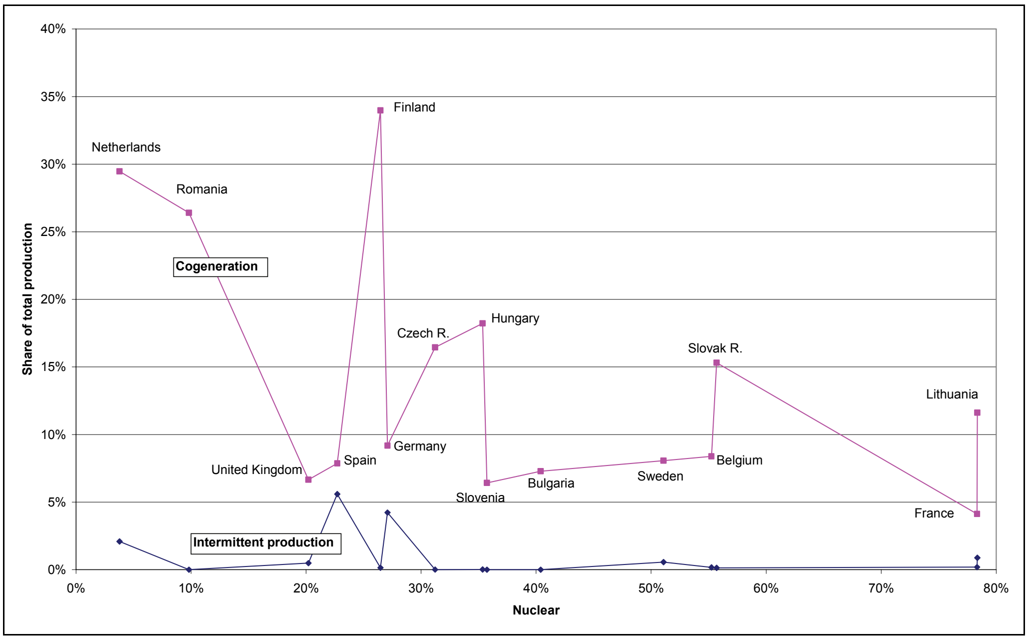

Fig. 18: Cogeneration's and intermittent production's share of total electricity production as a function of the nuclear share of total electricity production.

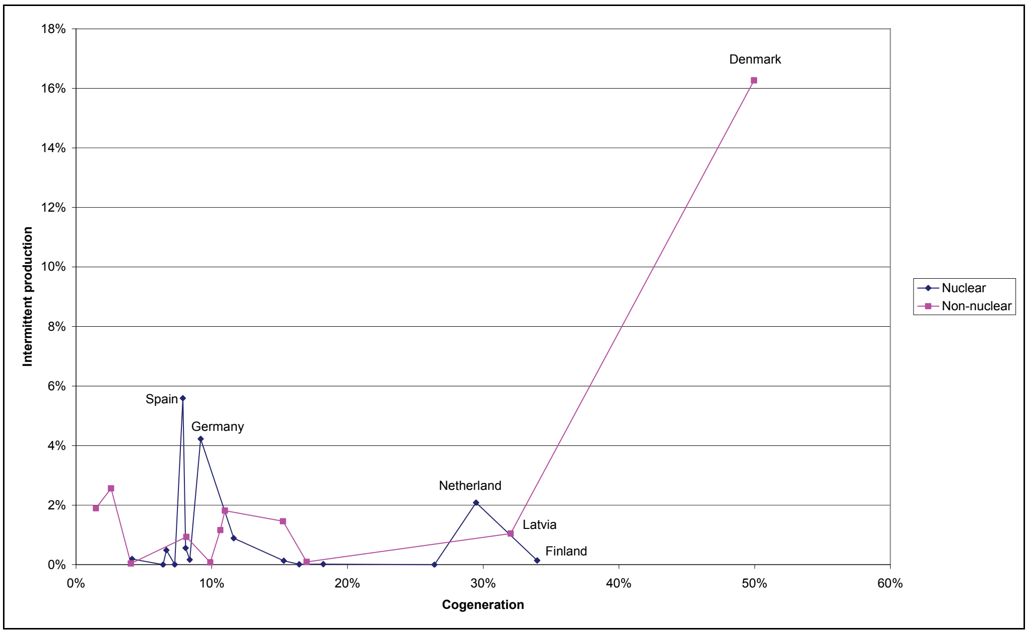

Fig. 19: Intermittent production's shares of total electricity production as a function of cogeneration's share of total electricity production.

In 2005, France, Germany and Italy accounted for 73% of the aggregated EU public energy R&D funding. France has the largest energy R&D budget in EU-25 from which nuclear research takes up more than 60% of the total budget in 2005, by which it is clearly indicated that France's future focus is the continuation of its nuclear legacy. "[France's] national advantages need to be highlighted [in a common EU energy policy] (nuclear plants competitiveness, CO2 emissions, renewable energies, white certificates, etc.). Thus, France might evolve from "black sheep" to an energy model based on better energy intensity, energy independence, low electricity costs, energy capacities storages and low emissions.", writes research Paris Dauphine about France's stance on an European energy policy in Energy Policy in 2007 [60]. Fairly, France is working on several fronts, and assigns considerable research resources for other low-carbon technologies than nuclear reactors, including biomass use, solar and geothermal energy, carbon capture and storage, and energy efficiency.

Current projections and existing R&D strategies suggest the existence of three basic territories for sustainable energy exists: *nuclear/hydro*, *coal with sequestration*, and *intermittent renewables in combination with distributed generation.*

As for EU, the combined mapping of energy R&D in member states concludes that 40% is dedicated to nuclear energy, 20% to renewables, and some 10% to fossil fuels and energy efficiency. As for the world, a tallying of public research priorities in US, Japan, and EU, reveals the dominating attention nuclear and fossil strategies for sustainable energy receives (Fig. 20).

It is evident that a nuclear strategy for sustainable energy is currently followed by France and United Kingdom, hybrid strategies are followed by German and Italy, Poland has no strategy, and the CO2 sequestration strategy is in play, with Germany and Italy investing heavily here.

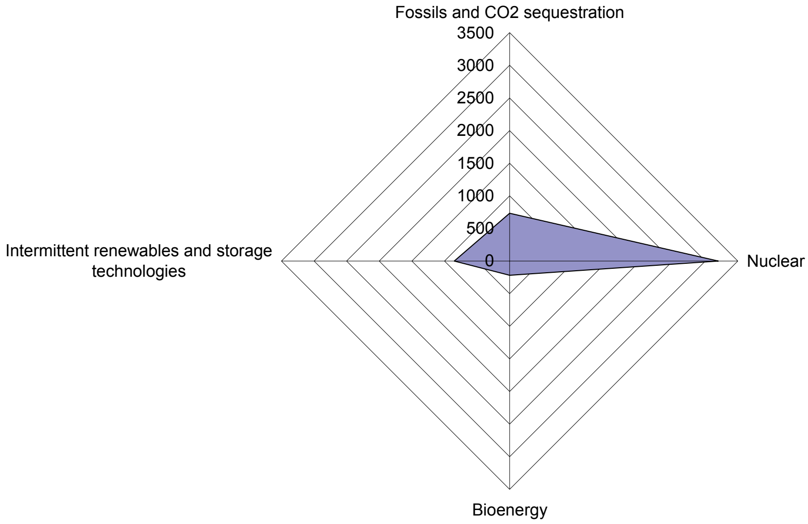

Fig. 20: Total public R&D spending in Japan, USA, and EU-13 grouped by sustainable energy system solutions (mill. EUR). Based on own categorization of data from the European Commission [59].

What would be a wise sustainable energy strategy for Denmark?

3.5 The coming of dawn

Firstly, Denmark needs to acknowledge the balance of power between basic strategies towards sustainable energy, as it is evident that one of these strategies, intermittent renewables in combination with distributed generation, receives a relatively minor share of interest and resources.

Secondly, Denmark needs to acknowledge that nuclear power has already entered the Danish territory by cross-national electricity markets, and that any open access strategy for integration of intermittent resource will also allow for increasing the share of nuclear energy in the Danish energy supply. In the light of the current power balance, and the incompatibility of these strategies with a foreseeable future, this is threatening conditions for following through on a strategy based on intermittent renewables in combination with distributed cogeneration.

Thirdly, today, the transmission system is considered primarily a market place in all its glory, a battlefield for economic interests, hosting the idea that expanding and opening the transmission system spirits liberalization. But in fact, the transmission system is developing into a battlefield for incompatible strategies for sustainable energy.

With the climate crisis unsolved, basic sustainable energy strategies should be considered in their own right, as potential solutions, and evaluated in context. This essay argues that a common goal for the world for mitigating carbon dioxide emissions does not imply a common solution. In fact, I have reached the understanding that the global effort to solve the climate crisis, in effect of acknowledging fundamental uncertainty and risk, and the entirely different contexts on the basis of which options for solving the climate crisis appear, will require for the global community to serve and protect a multi-contextual experimental strategy to handle the climate crisis.

Denmark is in a unique position by global comparison for investigating whether it is doable and feasible for intermittent renewables to be combined with distributed generation thereby contributing to solving the climate crisis. The Danish exergy experiment is paradigmatic in a global context providing unique experiences of global importance.

These reflections leads me to conclude this essay by calling for Denmark to formulate a sustainable energy policy that defends and follows through on a domestic integration strategy for large-scale penetration intermittent wind power in combination with distributed cogenerators. Above current penetration rates, this is going to require technological energy system innovations. The thesis basically takes upon itself to contribute in this field.

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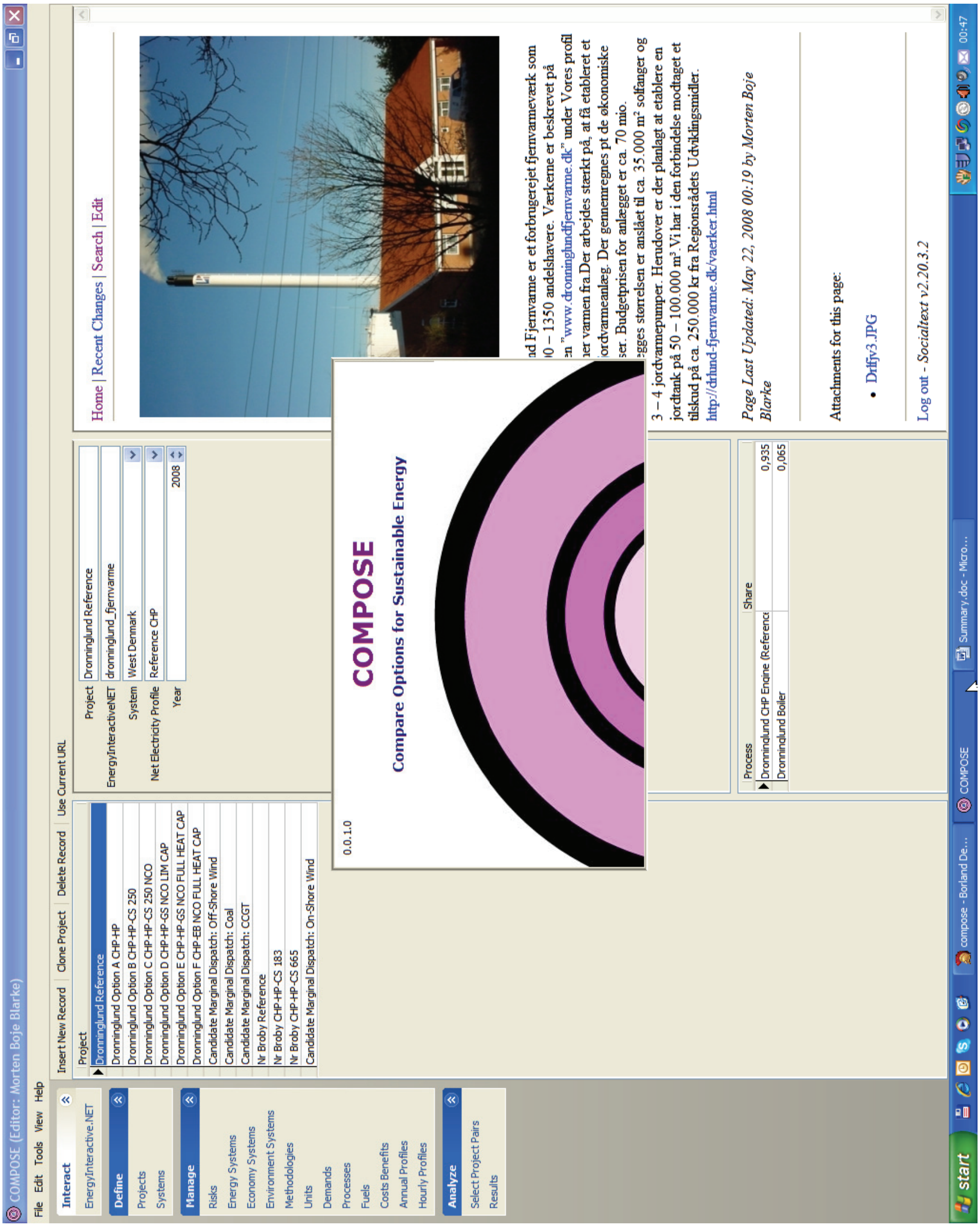
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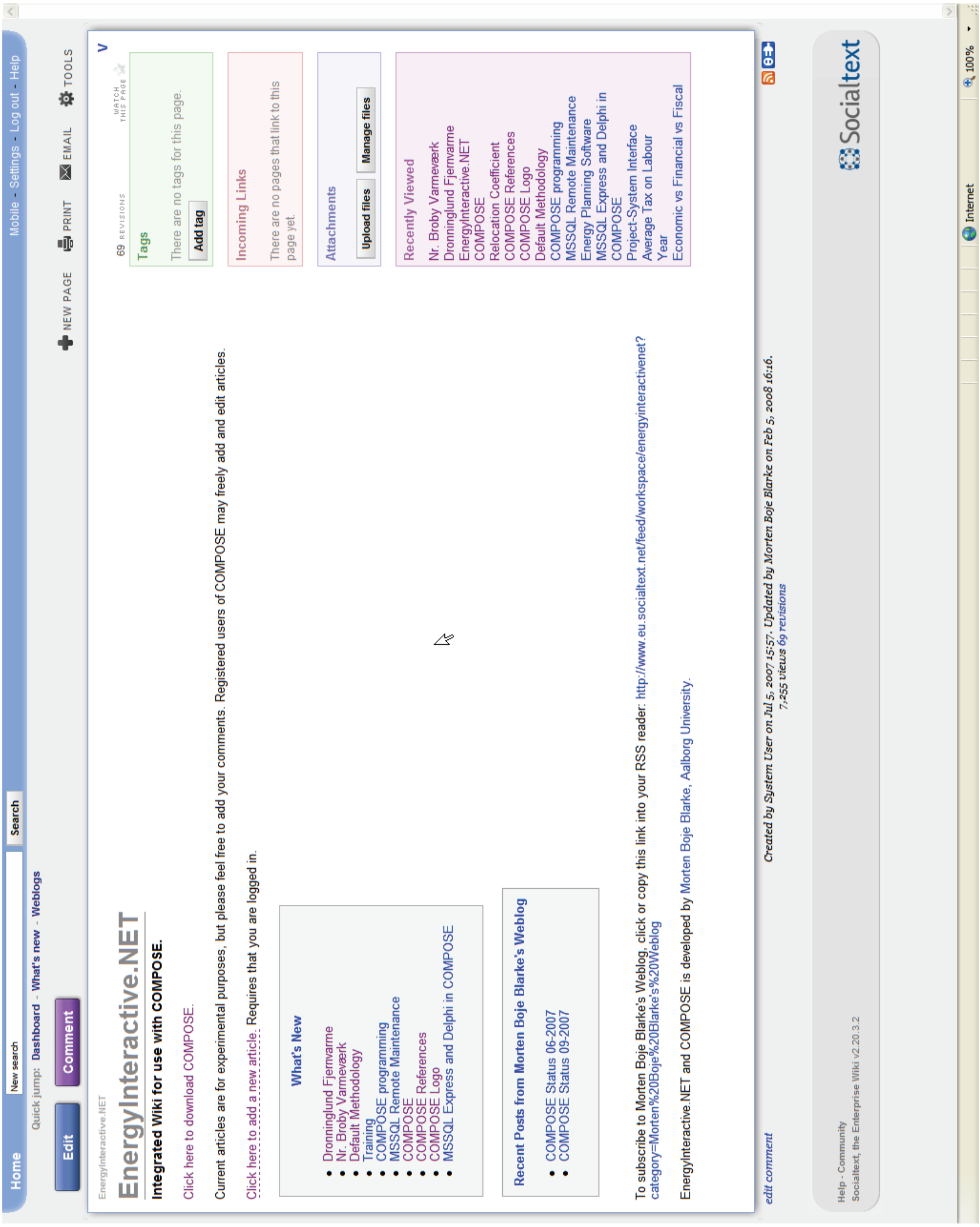
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Fjernvarmeværker forventer fremtid med elpatroner

Nu kommer den helt forureningsfri fjernvarme - men er elpatroner vejen til verdens reneste og mest effektive energisystem?

ELVARME

Af Ph.D. Morten Boje Blarke, Aalborg Universitet

Det går godt for de danske fjernvarmeproducenter, den sidste bastion for avance-fri forbrugereje i energisektoren. Ny-liberalismen har ikke fodfæste her, og fjernvarmeforbrugerne kan efter en kold vinter med høje brændselspriser generelt glæde sig over at have haft adgang til landets billigste varmeforsyning.

Men høje brændselspriser og store udsving i indtægter fra elsalg stiller fjernvarmeproducenterne i en følsom situation, som kræver fremsynet handling.

Hovedmål: Risiko-minimering

En aktuel mulighed for risiko-minimering på produktionssiden er at investere i elpatron eller varmepumpe. Både selskabsøkonomisk og samfundsøkonomisk er der et stort potentiale for elanvendelse i fjernvarmeproduktionen. Selskabsøkonomisk fordi det giver en større fleksibilitet i brændselsanvendelsen, samfundsøkonomisk fordi det bidrager til at indregulere stigende mængder vindkraft og kraftvarme.

FAKTA

- Forskere fra Aalborg Universitet og Teknologisk Institut har i samarbejde med Dansk Fjernvarme undersøgt værkernes holdning til elanvendelse i fjernvarmesystemer.
- Dansk Fjernvarme har i alt 402 medlemsværker. 61 deltog i undersøgelsen, heraf 42 med kraftvarmekapacitet.

National indsats

Det var netop disse samfundsøkonomiske perspektiver, der lå til grund for de ændringer af miljø- og energiafgiftslovene, L81, som Folketinget vedtog den 16. december 2005.

L81 ligestiller elanvendelse med anden brændselsanvendelse i fjernvarmeproduktionen. Med forbehold.

Dels skal den momsregisterede fjernvarmeproducent kunne dokumentere kraftvarmekapacitet, dels må kraftvarmeanlægget ikke samtidig fremstille el.

Økonomisk fungerer ligestillingen på den måde, at der er fastsat en maksimal afgiftsbetaling på 45 kr. per GJ fjernvarme ab værk. Før L81 ville det have kostet 160 kr. i afgift at fremstille 1 GJ fjernvarme fra el med elpatron, en afgiftsbesparelse på godt 70%. For varmepumper ser regnestykket ikke så fordelagtigt ud.

Før L81 ville det have kostet måske 50 kr. i afgift at fremstille 1 GJ fjernvarme fra el med varmepumpe, en afgiftsbesparelse på blot 10%.

Afgørende er det, at L81 baserer sig på en beskatning af varmeproduktionen ab værk. Det er med andre ord ligegyldigt, rent beskatningsmæssigt, om der anvendes 1 kWh eller 3 kWh elektricitet for at producere 3 kWh varme. Energi- og miljøafgiften beregnes på basis af produktionen, dvs. 3 kWh varme. L81 tilskynder således ikke til effektiv elanvendelse, iøvrigt med den konstruerede begrundelse, at effektiv elanvendelse ikke fører til CO_2-reduktioner i EU's kvotesystem. Kvotesystemets økonomiske teori begrunder, at hvis CO_2-udledningerne stiger et sted, vil de falde et andet sted. CO_2-udledningerne stiger altså ikke ved øget elforbrug, da kvotemængden ikke ændres. Ingeniører kan blot konstatere, at en oplagt mulighed for at fremme den mest effektive energianvendelse forbigås.

Skal løse eloverløbsproblem

L81 skal bidrage til at løse det problem, at elproduktionen i perioder overstiger den indenlandske efterspørgsel. Den stigende overskudsproduktion er et resultat af planer om at øge vindkraftens andel af den samlede elproduktion, konkret til 25 % i 2010, og den fortsatte satsning på samproduktion af kraft og varme.

Overskudsproduktionen betyder, at bunden i perioder går ud af elmarkedet, hvilket er en trussel mod forsyningssikkerheden på længere sigt. L81 har til hensigt at afhjælpe dette problem ved at gøre det attraktivt at anvende el i fjernvarmeproduktionen ved samtidig nedregulering af varmebunden elproduktion. Dermed danner L81 et sikkerhedsnet for elproduktionen og skaber basis for indregulering af vindkraft på markedsvilkår.

Hvad gør varmeproducenterne?

På denne baggrund har forskere ved Aalborg Universitet og Teknologisk Institut, i et samarbejde med Dansk Fjernvarme, gennemført en undersøgelse, der skal afdække, hvordan fjernvarmeproducenterne aktuelt stiller sig til elanvendelse i fjernvarmeproduktionen.

Undersøgelsen viser, at næsten hver tredje fjernvarmeproducent finder det sandsynligt, at man vil installere en elpatron eller en varmepumpe inden for 3-5 år. Dette falder sammen med, at fjernvarmeproducenterne generelt forventer stigende efterspørgsel på varme, og helt overvejende mener at have en tilfredsstillende økonomi.

Undersøgelsen viser dertil, måske ret overraskende, at varmepumpeteknologien har producenternes udbredte bevågenhed, til trods for, at der ikke er udsigt til at varmepumpeteknologiens termodynamiske fortræffeligheder vil blive omsat i særlige afgiftsmæssige incitamenter. Det er i hvert fald ikke sket med L81.

Undersøgelsen peger samlet set på, at elanvendelse i fjernvarmeproduktionen står over for et markant gennembrud. Og alt imens man kan diskutere, om ikke fravalget af økonomiske incitamenter for valg af varmepumpe frem for elpatron er et fejlgreb, der skæmmer en tværpolitisk vision om, at Danmark skal udvikle verdens reneste og mest effektive energisystem, så viser undersøgelsen, at danske fjernvarmeproducenter er særdeles interesserede i varmepumper og gerne vil være med til at udvikle de mest effektive anlægsløsninger. Hver anden fjernvarmeproducent vil således gerne være vært for et demonstrationsprojekt for varmepumper.

Aalborg Universitet, Teknologisk Institut, Dansk Fjernvarme, og andre aktører, arbejder på at skaffe midler til sådanne demonstrationsprojekter.

Planer om elanvendelse

I undersøgelsen blev der spurgt til fjernvarmeproducenternes forventninger til L81. Besvarelserne viste, at 85 % af producenterne slet ikke eller kun i mindre grad oplever at være bekendt med afgiftsændringen. 10 % forventer at afgiftsændringerne vil få "stor betydning".

Om end det altså ikke af flertallet vurderes at være af "stor betydning", så fandt lige under 30 % det sandsynligt, at man vil installere en elpatron eller en varmepumpe, typisk i løbet af 3-5 år. Om end fjernvarmeproducenterne overvejende finder det sandsynligt, at man vil installere en elpatron, så vil 35 % af dem, der forventer at installere en elpatron, lige så gerne installere en varmepumpe.

Den største gruppe svarer imidlertid "Ved ikke" til spørgsmålet om fremtidig elanvendelse og giver dermed udtryk for et uafklaret forhold til elanvendelse. Supplerende spørgsmål viser, at der især er usikkerhed om de selskabsøkonomiske konsekvenser.

Planer om anlægseffekt

De fjernvarmeproducenter, der fandt det sandsynligt eller sikkert, at man vil installere elpatron eller varmepumpe, blev derpå spurgt til hvor stor en anlægskomponent, der formentlig vil blive tale om. Budene varierede fra 0,1 MW varmeeffekt og helt op til 30 MW varmeeffekt. Ved at krydse besvarelserne med Energistyrelsens stamdata, fremgår det, at producenterne i gennemsnit forventer at installere 0,4 MWe eleffekt per installeret MWe elkapacitet. Spredningen er fra 0,1 MWe til 2,6 MWe per installeret MWe elkapacitet. Forholdes anlægskomponentens størrelse til den installerede varmekapacitet inklusiv kedler, findes, at producenterne i gennemsnit forventer at installere 0,4 MWe eleffekt per installeret MW varmekapacitet, maksimalt 0,8 MWe per installeret MW varmekapacitet.

På spørgsmålet om hvad der kunne være relevante lavtemperatur-varme-

(Fortsættes næste side)

(Fortsat fra forrige side)

kilder for en eventuel varmepumpe, viste producenterne stor interesse for røggaskøling og intercooling. Således mente 85 %, at en varmepumpe kunne integreres med henblik på samtidig drift og generelt bedre udnyttelse af kraftvarmeenheden.

For varmekilder, der ikke kræver samtidig produktion på kraftvarmeenheden, svarer 60 %, at man i større eller mindre grad opfatter solvarme eller udeluft som en mulighed. 40 % svarer, at jordvarme og spildvarme/spildevand vil være en mulighed, mens 20 % peger på geotermi.

Varmepumpe kontra elpatron

På spørgsmålet om, hvad der opleves at være af særlige problemer for varmepumpe i forhold til elpatron, mener 20-25 % at den fysiske placering, samt den tekniske og driftsmæssige integration, til en vis grad kan være et problem for varmepumpen. Et flertal oplever dog ikke, at der er problemer af teknisk eller fysisk karakter forbundet med en varmepumpeløsning frem for elpatron.

Fjernvarmeproducenterne er imidlertid enige om at være usikre på de selskabsøkonomiske konsekvenser. Over 90 % angiver, at man enten ikke kender til, eller i et vist omfang er skeptisk over for såvel investeringsrisiko som rentabilitet for varmepumpe sammenlignet med elpatron.

Alligevel svarer 45 %, at man i nogen eller høj grad vil være interesseret i at indgå i samarbejde om et demonstrationsprojekt for varmepumpe, hvoraf omkring halvdelen samtidig vil deltage med medfinansiering og være indstillet på en økonomisk risiko.

Hvad angår andre virkemidler mente cirka 75 %, at det i nogen eller høj grad kunne få afgørende betydning for interessen for varmepumper, hvis der blev ydet særlig afgiftslempelse for køb af el til varmepumpe eller direkte investeringstilskud.

Konklusion

Om end L81 alene giver afgiftsreduktion for elanvendelse uden samtidig elproduktion, så repræsenterer konceptet med kombineret varmeoptag, både fra kraftvarmeenhed og fra ekstern lav-temperatur varmekilde, f.eks. jordvarme eller udeluft, en yderst effektiv og robust løsning, både for fjernvarmeproducenten og for energisystemet. Selskabsøkonomisk afhænger meget af den konkrete anlægsintegration og prisudviklingen på el og f.eks. gas, men det er muligt at opnå tilbagebetalingstider på under 6 år, måske helt ned til 3-4 år. For så vidt angår investeringsrisiko, så er det en individuel vurdering, om ikke den højere anlægsomkostning for varmepumpen opvejes af større robusthed over for ændringer i elprisen. Fremtidige undersøgelser har til hensigt at analysere vilkår for konkrete værker.

Det er imidlertid en forudsætning for den videre udvikling, at der afsættes midler til at afprøve disse løsninger i praksis i form af fuld-skala demonstrationsanlæg. Samfundsøkonomisk er der indiskutabelt store perspektiver for varmepumpeteknologien, frem for elpatroner, ikke mindst fordi effektiv elanvendelse også giver plads til udvikling af ny elforbrugende teknologi på andre områder, f.eks. brintproduktion og elbiler, da elpatroner i højere grad end varmepumper vil "støvsuge" markedet for billig el.

Dette gør samlet, at varmepumpen bør være en højt prioriteret løsning for elanvendelse i fjernvarmesektoren. Og både teknologi, fjernvarmeproducenter, og videnscentre, melder sig klar til at afprøve konceptet i fuldskala.

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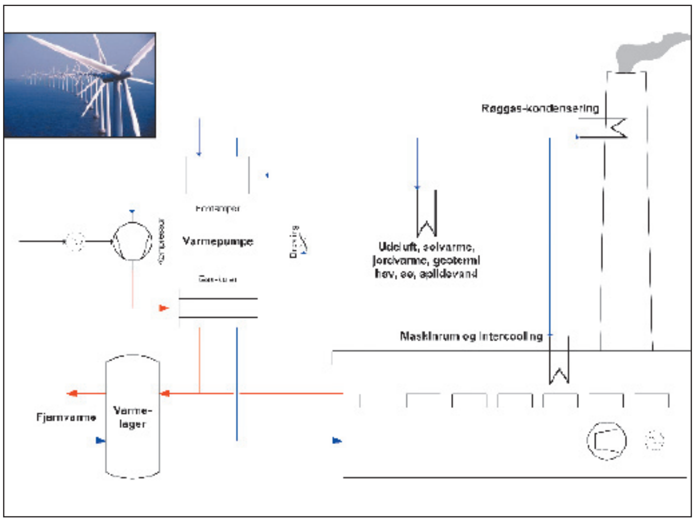
KONCEPT FOR VARMEPUMPE

KONCEPT FOR VARMEPUMPE

Den aktuelle interesse for varmepumper skyldes især, at ny varmepumpeteknologi ser ud til at blive et gennembrud for fjernvarmesektoren.

Med en fremløbstemperatur på 85 °C kan den transkritiske CO_2-varmepumpe således levere fjernvarme uden bidrag fra andre enheder og med en årsmiddel-effektfaktor på mellem 2 og 4, afhængigt af lavtemperaturvarmekilden, lavest for udeluft, opnås en uovertruffen høj termodynamisk effektivitet.

Figuren herunder illustrerer princippet for den overordnede system- og anlægsintegration, som der arbejdes på.



Koncept for system- og anlægsintegration med eksisterende kraftvarmeværk: Varmeoptag fra røggas, maskinrum og eksterne kilder. Transkritisk kølekreds med eldrevet kompressor, der muliggør varmepumpedrift med eller uden samtidig drift af kraftvarmeenhed.

Interactive energy planning: Towards a sound and effective planning praxis

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Keywords: planning, interactivity, context, power, rationality

Abstract

Though it is being questioned whether planning theory should be fitted into neat typologies, some have described evolving planning theory as a journey away from ethnocentrism, through the lands of rationalism, pragmatism, socio-ecological idealism, political-economic mobilization, currently anchoring along the shores of the land of communications and collaboration. Whether or not a particular typology is applicable, theory and praxis are establishing standpoints, which strengthens our understanding of the planning complex, and which should inspire improved energy planning methodologies and tools.

This paper presents an “Interactive Energy Planning” framework, which is intended to support interactivity in planning, building on important theoretical and experimental advances in planning. In particular, the paper explores the potential significance of allowing a critical perspective on context analysis and problem-orientation to define the course of the planning process, and deploying value-rational planning tools primarily as a platform for interactivity.

The focus on interactivity in energy planning will allow contemporary government planners, consultants, researchers, and organizational managers more effectively to address important technical and economic problems.

Interactivity drives innovation

It is not neo-classical economic theory, but rather the praxis of political intervention and institutional change that helps to explain two recent innovations in European energy policy; Denmark’s success with wind power (Lauber, 2006b), and UK’s success with curbing urban traffic in London (Livingstone, 2004).

In fact, the widespread application of neo-classical economic theory in contemporary policy making may lead us to be overlooking crucial options for innovation, as institutional and technological path dependence and lock-in situations are not effectively dealt with, or perhaps not even recognized. Neo-classical economic theory favors the idea that preferences of various agents are constant and comparable, and that decisions are reversible and predictable according to a process of benefit maximization. But real life decisions are otherwise complex and irreversible, individuals and institutions are prone to routines and habits, but may also act creatively.

Neo-classical economic theory’s indifference to the mechanisms of power and the nature of technology, its’ marginalization of institutional and technological path dependence and lock-in situations, reveal its' incapability to explain the effectiveness of policies that supports innovation by regulating markets rather than de-regulating them (Lauber, 2006a).

In original institutional economic theory it is suggested that individual and institutional preferences are specific and contextual, generally prone to routines and habits, but most importantly, not based on trivial rational calculation, but rather on judgment that is generated by creation and coordination of expectations through social interaction (Nielsen, 2005).

The notion of interactivity is also central in Michel Foucault's works, who has made a convincing case about the way truth, and reason, is coupled with power and epistemology. Foucault uses a historical narrative to provide us with a theoretical basis for understanding the way rationality and power works to produce knowledge and "truth". According to Foucault, planners should find that many given "truths" are temporary outcomes of historical conflicts currently nesting within networks of power, and are either in line with or in opposition to the planning context itself. In order to understand and possibly influence particular decisions about technology choice and socio-economic development, planners are required to seek clarity about these conflicts through the eyes of both an internal and external context, while critically analyzing the mechanisms of power being exercised, truths being established. Foucault makes it clear that global structures of power, interests, and values, are best analyzed by looking at local tactics of domination, concretely by the way people interact along the borderline of their reign (Foucault, Bertani, Fontana, and Ewald, 2003).

Such focus on interactivity is in opposition to many widely applied energy planning frameworks, like Integrated Resource Planning (Shrestha and Marpaung, ;Swisher and Januzzi, 1997), which unilaterally focuses on making techno-economics generally applicable to produce the value-drivers needed in dealing with particular decision problems.

Such focus on instrumental rationality has possibly contributed to the experience that "planners and other agents of intervention continue to make assumptions about the values, beliefs, or rationalities of those for (or with) whom they plan, which frequently do not hold" (Watson, 2003).

In response, planning theorists are calling for planners to embark on story telling practices (Richardson, 2005), suggesting for the planner to become a narrative explorer placed in context, uncovering the mechanisms of power by searching for the "truth" in the detail (Flyvbjerg, 2004).

Though it is being questioned whether planning theory should be fitted into neat typologies (Richardson, 2005), some planning theorists (Lawrence, 2000) have furthermore described evolving planning theory as a journey away from ethnocentrism, through the lands of rationalism, pragmatism, socio-ecological idealism, political-economic mobilization, and currently anchoring along the shores of the land of communications and collaboration.

This paper attempts to bring together in a single planning framework basic questions in energy planning, including those that deals with power, winners and loosers, with the move towards the communicative and collaborative in planning.

An interactive planning framework

Flyvbjerg (Flyvbjerg, 2004) suggest for planners to recognize the basic questions in planning as being:

1. Where are we going?
2. Who gains and who loses, and by which mechanisms of power?
3. Is this development desirable?
4. What, if anything, should we do about it?

The intention of asking such basic questions is to allow for the process of social interaction in context to shape not only the formulation of the decision problem, but also the formulation of objective, the appreciation of alternatives, as well as the nature of the outcome.

Besides adding the question of "Where are we now?" (and with this question also often the question: "How did we get here?"), the proposed framework builds on three pillars of understanding in planning: Context as a social construct formed by historical and cultural appropriation; Social interaction as a riskful transaction between conflicting interests through which emotions, rationality, and power, synthesize to become episteme; and Creativity as inherent to a sound human environment by means of which individuals and institutions expresses innovative capabilities.

Thus, Figure 1 illustrates planning as a circular process of communicating contexts, problem, objective, trends, options, instruments, policies, and strategies for intervention.

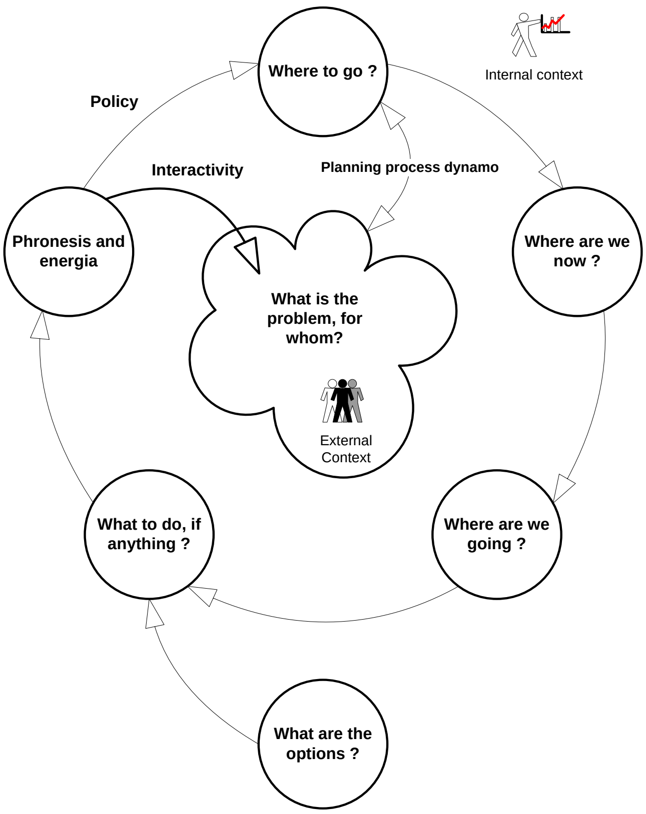

Figure 1: An interactive planning framework; a circular process of communicating contexts, problem, objective, trends, options, instruments, and strategies for intervention.

Figure 2 illustrates that each step in the planning process is an interface for interaction between agents, either within the internal context (the planning team), within the external context (the problem field), or inbetween the internal and external context.

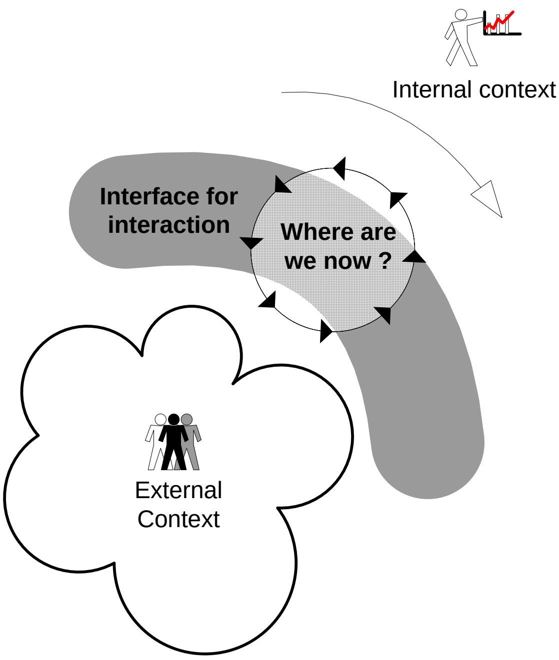

Figure 2: Each step in the planning process is an interface for interaction.

The practical challenge in interactive energy planning becomes to address, map, and document the interaction that has, is, and will be taking place over the course of the planning process. The analytical challenge is to name and unmask dysfunctional games, as well as to deconstruct situations in which one agent exercises power over another agent, with or without consentual contracts.

An example of a dysfunctional game in energy planning is the situation in which one agent uses an embedded historical technical and economic rationality to limit another agent's intent to innovate, and this agent attacks the first agent's rational basis, the "You cannot do what I do < > You have no reason to claim that" game. For example, in December 2003, an Irish grid operator announced that they would accept no more electricity from wind farms, because wind power was unmanageable and grid failures would be inevitable (Courtney, 2006). In response, the chairman of the Wind Energy Association held that the assumptions for this decision were "fundamentally flawed", without any further clarification (Murray, 2004).

While dysfunctional games may serve the involved interacting agents, protecting them from the intimidating reasoning of other agents, it does not serve the greater societal purpose, which is to stimulate creativity and innovation. Thus, such games need to be addressed by planners and policy makers.

In interactional planning, agents' real objectives is unmasked by naming games, possibly calling power bluffs, and addressing the underlying rationality by analysis, without judging them by any single institutional or professional interest.

Serving a deconstructive purpose, interaction may be modeled as transactions between agents, originating from learned behavior and rationality; according to the agent's role as institution, citizen, and human, as illustrated in Figure 3.

Aligning with its origin in psychology's field of transaction analysis, the interactional planner's challenge becomes to bring about individual and institutional relationships of the type "I am ok, you are ok" (Berne, 1964). The fundamental hypothesis is that such position is the most effective basis for allowing creativity and innovation to thrive, by the mechanism of stroking agents through recognition and communicating that change is possible.

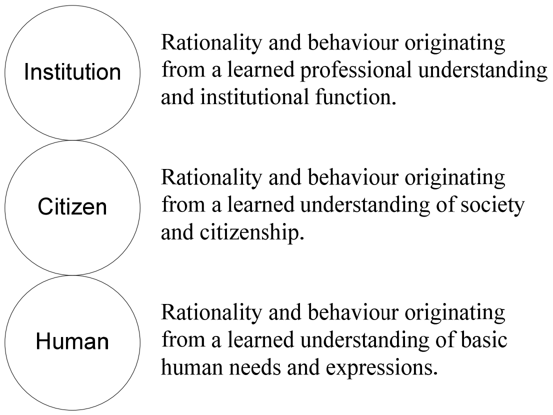

Figure 3: The agent; Behavior and rationality originating from learned understanding of three archetypes: institution, citizen, and human.

The concept of interactive energy planning should inspire planners to spend less time in “The world is mine < > Yes, but not in my utopia” and other dysfunctional games, and more time analyzing the basis for internal and external rationalities, allowing for interventions into interactions to support value-rational change.

Technical and economic analyses are not always relevant, and certainly never adequate in approaching a decision problem. Interactivity as a theoretical and methodological platform relies on a basic cross-disciplinary planning framework with particular emphasis on the analysis of interaction between agents. The challenge is to use the analysis of interactions as an instrument for intervention that leads to the establishment of open and sober communication between citizens allowing each other the potential to innovate.

Towards inclusive and cross-disciplinary planning frameworks

In perspective, interactive energy planning is intended to prepare for a shift towards inclusive and cross-disciplinary analytical frameworks and institutional designs. Interactive energy planning requires the involvement of multiple professional disciplines: economists, engineers, politologists, sociologists, psychologist, historians, and educators - as no single profession should be made responsible for handling complex analytical problems related to social and technological change.

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Store varmepumper med koldt varmelager i forbindelse med eksisterende kraftvarmeproduktion (CHP-HP Cold Storage)

Kontekst

Konceptet retter sig mod kraftvarmeproducenter i fjernvarmesektoren, der i indsatsen for at opnå højere virkningsgrader i produktionen, overvejer at installere en varmepumpe med henblik på yderligere udnyttelse af røggasvarme ved kondensering. Men som på grund af afgiftsreglerne alene vurderer en løsning med mekanisk/hydraulisk udveksling mellem motorenhed og varmepumpe, ikke en elektrisk. Og som dermed forspilder chancen for et anlægskoncept, der ved selvstændig drift af varmepumpe kan resultere i en selskabsøkonomisk og samfundsøkonomisk fleksibel og optimeret produktion, herunder systemteknisk yde et bidrag til indregulering af vindkraft og kraftvarme.

Formål

CHP-HP Cold Storage konceptet med elektrisk dreven varmepumpe bidrager til problemløsning på 2 fronter:

1. Et løfte om mere effektiv brændselsudnyttelse i forbindelse med kraftvarmeproduktion. Ved samtidig drift af kraftvarmeenhed og varmepumpe øges værkets totalvirkningsgrad signifikant, i et konkret skitseprojekt fra 91,8 % til 96,8 %, altså 5 % -point,
2. En mulighed for systemindregulering af vindkraft og kraftvarme. Med et koldt varmelager til lagring af kondenseret røggasvarme, eller med et alternativt lav-temperatur varmeoptag, gives mulighed for effektiv elanvendelse i fjernvarmeproduktionen ved drift af varmepumpe uden samtidig drift af kraftvarmeenhed.

Dertil vil konceptets introduktion af nyt brændsel (elektricitet) i fjernvarmeproduktionen øge værkets og systemets økonomiske robusthed overfor forandringer i el- og brændselsmarkeder.

Udover given teknisk mulighed for indregulering, er en elektrisk-dreven varmepumpe at foretrække frem for mekanisk eller hydraulisk udveksling af flere grunde: mindre tab ved kraftoverførsel, lavere anlægsomkostninger, samt større selskabsøkonomisk og samfundsøkonomisk værdi af at introducere uafhængig og fleksibel elanvendelse og elproduktion i forbindelse med fjernvarmeproduktion.[1]

Funktionsprincip

Elektrisk-dreven varmepumpe, der opererer transkritisk med mulighed for fremløbstemperaturer over 80 grader celsius, dvs. et temperaturniveau som fjernvarmesektoren efterspørger, og som derved i praksis giver mulighed for fjernvarmeproduktion fra varmepumpe uden samtidig kraftvarmeproduktion. Lav-temperatur varmebidrag opnås ved kondensering og lagring af røggas med option på yderligere lav-temperatur varmeoptag, f.eks. jordvarme (Figur 1). Konkret

[1] Da en mekanisk/hydraulisk varmepumpe alene vil være i drift, når elprisen er høj.

driftsstrategi fastlægges af fjernvarmebehov i samspil med aftaler eller markeder for brændsler, elsalg, elkøb, og evt. balancemarked. Konceptet indgår i gruppen af relokeringsteknologier i et 2. generations bæredygtigt energisystem, som illustreret i Figur 2.

Teknisk potentiale

Teknisk potentiale for indregulering i det danske energisystem er godt 200 MWe[2] ved dimensionering med udgangspunkt i udnyttelsen af kondenseret røggas. I dette tilfælde indgår det kolde varmelager fra kondensering af røggas som begrænsende faktor for indregulering.

For at reducere den begrænsende faktor kan der etableres et kølebehov eller anden lavtemperatur varmekilde, f.eks. jordvarme. Derved vil anlægget kunne dimensioneres til maksimal varmeproduktionskapacitet,[3] hvorved det tekniske potentiale for indregulering øges til knap 900 MWe[4].

Selskabs- og samfundsøkonomisk potentiale

Detaljerede selskabsøkonomiske vurderinger er under udarbejdelse. De mest optimistiske resultater peger på, at der for konceptet, og dets afledte, ved avanceret drift kan opnås selskabsøkonomiske tilbagebetalingstider på 3-6 år, bedst for værker på markedsvilkår. Der henvises til:

1. PSO ansøgning om fuld-skala demonstrationsprojekt, det foreløbige resultat af samarbejdet på området mellem Teknologisk Institut, Aalborg Universitet, Advansor, Dansk Fjernvarme, Foreningen af Danske Kraftvarmeværker, og Naturgas Midt-Nord.

Detaljerede samfundsøkonomiske vurderinger er under udarbejdelse. Hidtidige vurderinger peger på et potentielt samfundsøkonomisk overskud, hvortil kommer et væsentligt perspektiv for beskæftigelse og erhvervsudvikling. Der henvises til:

1. Lokale Energimarkeder, Institut for Samfundsudvikling og Planlægning, AAU, 2004 (http://www.plan.auc.dk/publikationer/skriftserie.php?id=9&st=1)
2. Det fremtidige danske energisystem, Teknologirådet, 2006 (http://www.tekno.dk/pdf/projekter/p05_Danske_Energisystem_hoering-energiforbrug.pdf)

[2] Afhænger af decentral kraftvarmeffekt, her beregnet som 10 % af en effekt på 2000 MWe.
[3] Ifm. med solvarmeanlæg og sæsonlagring ifm. kraftvarmanlæg, vil der typisk også blive installeret en varmepumpe, hvis størrelse afhænger af solvarmeanlæggets dækningsprocent. Avancerede anlægskoncepter kunne sæsonlagre varmeproduktion også fra kraftvarmeenheden til brug for denne varmepumpe.
[4] Afhænger af decentral kraftvarmeffekt, her beregnet ud fra en Cm værdi på 0,60, en effekt på 2000 MWe, og en gennemsnitlig effektfaktor på 3,8.

Status for forskning og udvikling

Her henvises til

1. Artikel i Kraftvarmenyt nr. 82, august 2006, af Kim G. Christensen og Claus S. Poulsen, begge Teknologisk Institut http://plan.aau.dk/~blarke/downloads/vp_dckv.pdf.

Virkemidler

Det foreslås at:

1. Folketinget ved lov giver adgang til godtgørelse af afgift af op til 10 % af egenproduceret elektricitet anvendt i varmepumper til fremstilling af fjernvarme. Dette vil gøre det attraktivt at etablere en elektrisk-dreven varmepumpe med henblik på mere effektiv kraftvarmeproduktion, opnået ved røggaskondensering og samtidig drift af varmepumpe og kraftvarmeenhed. Dette virkemiddel kombineres driftsøkonomisk med L1417 ved drift af varmepumpe uden samtidig egenproduktion af elektricitet, der skal altså ikke kunne "spares op". Ideen er alene at det vil få kraftvarmeproducenter til at vælge en eldreven kompressor frem for mekanisk/hydraulisk udveksling. Med tanke på L1417 introduceres koldt varmelager, samt evt. yderligere varmeoptag, hvorved der etableres grundlag for en samlet set selskabsøkonomisk og samfundsøkonomisk optimal driftsstrategi for kraftvarmeværket.

2. Energinet.dk eller andre sponsorer bevilger midler til gennemførelse af et eller flere fuld-skala demonstrationsprojekter af konceptet, og dets afledte.

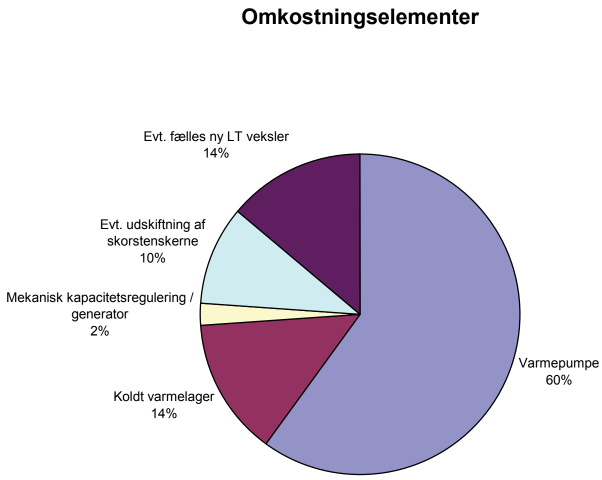
Samtidig anbefales det at:

- Folketinget ved lov introducerer en differentieret elafgiftslovgivning, som tilgodeser integrationen af vindkraft og decentral kraftvarme. Dette kunne f.eks. udmønte sig i en afgiftslovgivning, hvor der i perioder over året var adgang til godtgørelse af afgift for anvendelse af elektricitet til varmeproduktion i f.eks. frit opstillede varmepumper i forbindelse med sol- og jordvarme.

- Folketinget øremærker energiforskningsmidler til virksomheder og selskaber, der arbejder med løsninger, der anviser veje til integration af vindkraft og decentral kraftvarme. Især små og mellemstore virksomheder vil med støtte på det rigtige tidspunkt kunne udvikle innovative løsninger, der udover at løse væsentlige samfundsproblemer, skal sikre landets uafhængighed og konkurrenceevne i fremtiden.

Datablad (HP Cold Storage i forbindelse med eksisterende CHP)

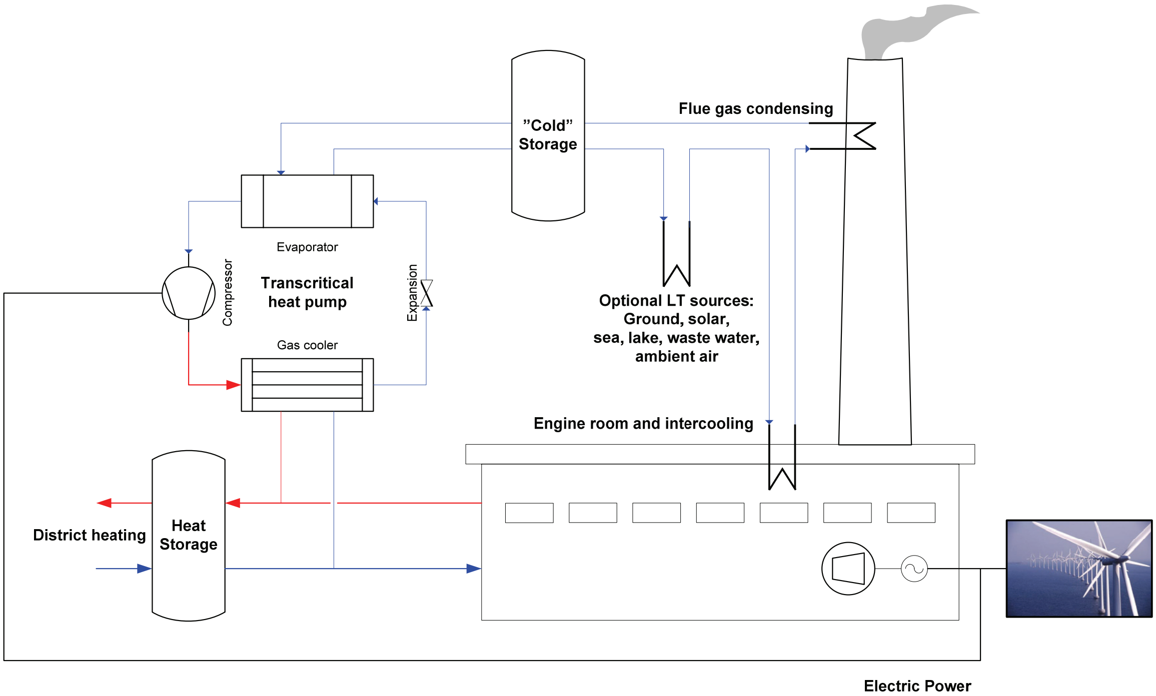
	Status	Vurdering scenarium	
	2006	Lav udbredelse	Høj udbredelse
Kølemiddel	CO_2		
Emissioner	Afhænger af elsystemets sammensætning og drift. Nødvendiggør systemanalyse for konkrete driftsstrategier samt udbygningsplaner for elforsyningen, herunder feedback effekt for udbredelse af koncept. Vurderinger under udarbejdelse.		
COP	3,7	3,8	3,9
Investering[5]	DKK 19,5 mio. per MWe	DKK 19,5 mio. per MWe	DKK 15,0 mio. per MWe
D&V	0[6]		
Levetid	20 år	20 år	25 år



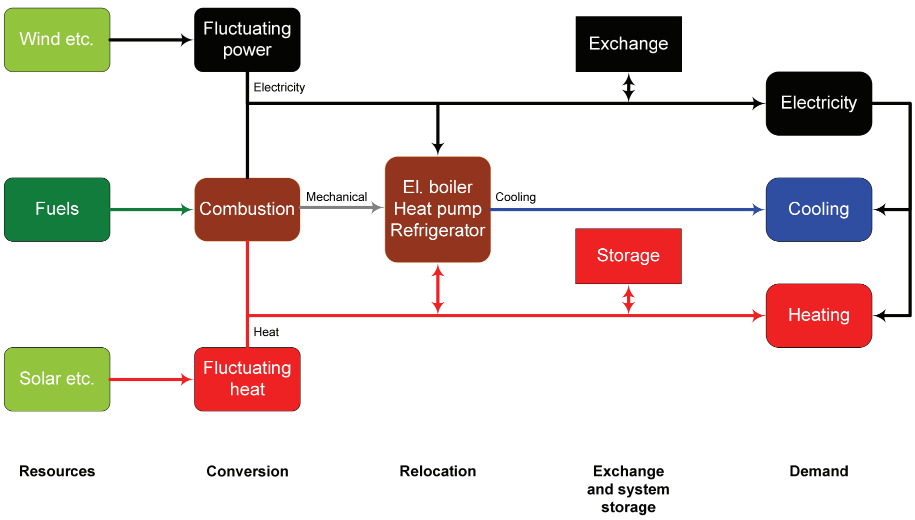
[5] Baseret på skitseprojekt til Dronninglund Fjernvarme med koldt varmelager og anlægsspecifikke installationer. Uden evt. jordvarmeanlæg. Jordvarmeoptag kan etableres for samme pris som en LT veksler: 1.200 kr/kW. Dertil kommer evt. pris for jordanvendelse.

[6] Meromkostning ift. eksisterende kraftvarmeproduktion. Baserer sig på en antagelse om at varmmepumpeanlæggets D&V omkostninger dækkes af D&V besparelser for kraftvarmeenheden.

Figurer



Figur 1: CHP-HP Cold Storage koncept. Kan kombineres med elpatron og solvarme.



Figur 2: Illustration af hovedelementer i et 2. generations bæredygtigt energisystem, hvor lagrings- og relokeringteknologi muliggør håndtering af fluktuerende energikilder, især vind.

NOTAT

Teknisk-økonomisk vurdering af kraftvarmepumpe-koncept til Dronninglund Fjernvarme A.m.b.A.

UDKAST

AALBORG UNIVERSITET

Institut for Samfundsudvikling og Planlægning
Morten Boje Blarke, Ph.D. Studerende
September 2006

Indholdsfortegnelse

Forord

Med udgangspunkt i undertegnedes og Dronninglund Fjernvarmes (DFV) deltagelse på Ingeniørforeningens møde i Aalborg, og efterfølgende oplæg til samarbejde, har DFV, Advansor, og undertegnede, gennemført en indledende undersøgelse og vurdering af perspektiverne for installation af dels varmepumpe, dels elanvendelse i forbindelse med Dronninglunds eksisterende fjernvarmeproduktion.

Informationer er indsamlet og analyser gennemført i perioden august-september 2006.

Analyser i dette notat er gennemført med Energi- og miljødatas EnergyPRO model samt med undertegnedes COMPEED model. I forhold til en sædvanlig selskabsøkonomisk analyse og investeringsanalyse, giver især COMPEED modellen mulighed for at inddrage miljømæssige, samfundsøkonomiske, og statsfinansielle konsekvenser i en integreret og konsistent vurdering.

Analysemodeller og datafiler er tilgængelige for DFVs brug.

Vurderingen, der hermed afrapporteres, gør det ikke ud for en konsulentrapport, men kan indgå som vejledende materiale i DFVs bestræbelser på at forbedre selskabets planlægning og drift. Der tages forbehold for fejl og mangler.

Advansor har rapporteret i eget notat.

Med venlig hilsen

AALBORG UNIVERSITY

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Sammenfatning

Opsummeret i 5 hovedpunkter, peger undersøgelsen på, at:

1. Det undersøgte kraftvarmepumpe-koncept, der baserer sig på en forenklet driftsstrategi, ikke er selskabsøkonomisk rentabelt for Dronninglund Fjernvarme. Mere avancerede driftsstrategier kan være rentable.

2. Det er ikke investeringsomkostningen, der er udslagsgivende for at det undersøgte kraftvarmepumpe-koncept ikke er selskabsøkonomisk rentabelt, men den konsekvens, som varmepumpen har for elsalget. Naturgasforbruget reduceres med DKK 442,000 årligt, mens indtægter fra elsalg reduceres med DKK 498,000 årligt som følge af den ændrede driftsstrategi af gasmotor. Der opnås således ikke en driftsøkonomisk besparelse med dette koncept. Igen skal det understreges, at der er regnet på et forenklet koncept, der ikke muliggør forskudt drift af varmepumpe.

3. Der er stor usikkerhed om naturgasprisens fremtidige udvikling, hvilket har afgørende betydning for rentabiliteten af investeringer, der fortrænger naturgasanvendelse. Den aktuelle naturgaspris gør at kedeldrift selskabsøkonomisk er 20 % billigere end gasmotordrift i højlast.

4. Det har ikke været muligt at eftervise den aktuelle driftsstrategi med det oplyste varmelagervolumen på 865 m3. Den aktuelle driftsstrategi – målte værdier – kan alene eftervises ved at anvende et korrigeret ”beregnet varmelagervolumen” på 500 m3. Dette tyder på at det eksisterende varmelager ikke fungerer optimalt. I den aktuelle situation har det dog ikke betydning for varmeproduktionsprisen, da et større varmelager alene giver mulighed for at øge produktionen i højlast, hvor kedeldrift aktuelt er billigere, som nævnt i punkt 3. Når naturgasprisen igen – som Energistyrelsen forventer – falder – vil et velfungerende varmelager bidrage til øge elproduktionen i højlast.

5. Og i den energipolitiske debat kan det være interessant at notere, at der til trods for statens mistede reducerede indtægter afgifter som følge af et reduceret naturgassalg, vil være et statsfinansielt overskud på DKK 350,000 p.a. ved investering og drift af kraftvarmepumpe-anlægget, hvilket især skyldes en antagelse om mer-beskæftigelse. Samtidig kan der være grund til at notere sig, at, under forudsætning af at den reducerede elproduktion på kraftvarmepumpe-anlægges opvejes af produktionsenheder indenfor CO_2-kvotesystemet, reduceres anlæggets og systemets CO_2 emissioner med 5 %. CO_2-skyggeprisen andrager på denne baggrund DKK 1.082 per ton CO_2.

1. Generelle teknisk-økonomiske forudsætninger

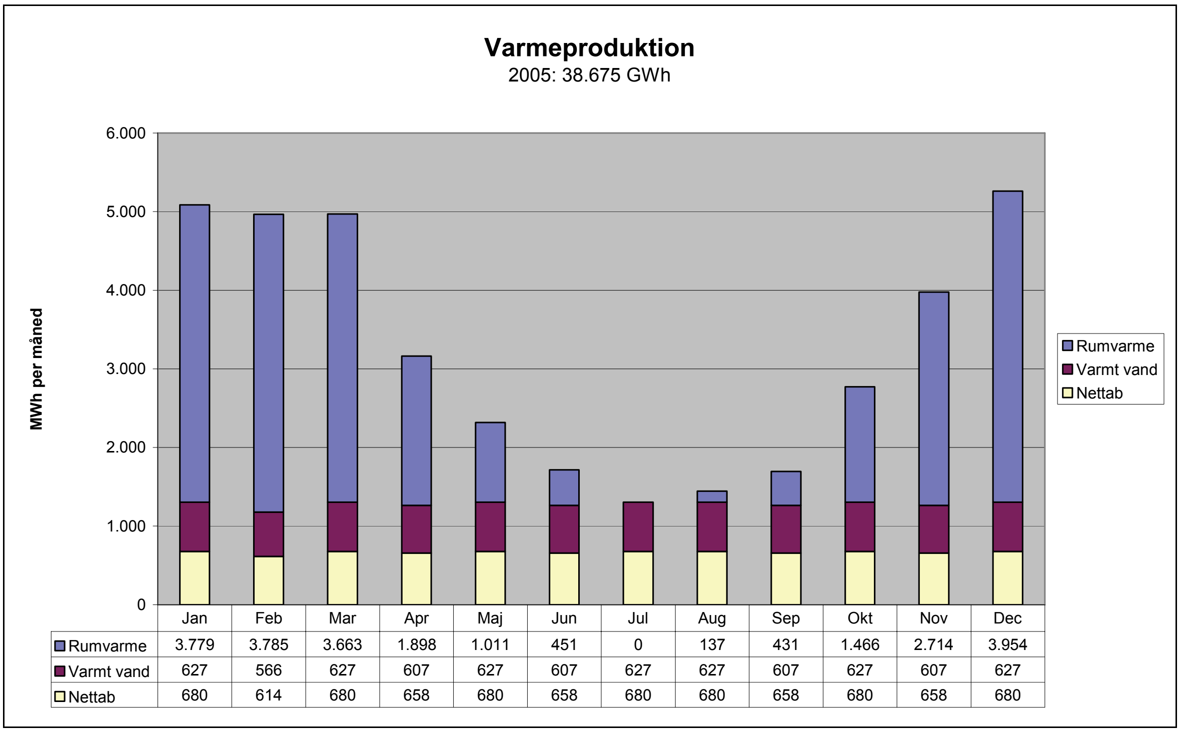
1.1 Overordnede forudsætninger og modelanvendelse

Følgende primære forudsætninger kan have betydning:

- Planperioden er på 20 år.
- Alle priser er angivet i danske kroner (DKK), faste priser (2006), hvis ikke andet er angivet.
- Inflationsraten er 3 % p.a.
- Den samfundsøkonomiske kalkulationsrente er 6 % p.a. realt.
- Den selskabsøkonomiske kalkulationsrente er 15 % p.a. realt.

1.2 Nuværende varmeproduktion og energianlæg

Figur 1 viser varmeproduktionens fordeling på rumvarme, varmtvandsforbrug og nettab. Varmeproduktion og fordeling antages konstant over planperioden.



	Jan	Feb	Mar	Apr	Maj	Jun	Jul	Aug	Sep	Okt	Nov	Dec
Rumvarme	3.779	3.785	3.663	1.898	1.011	451	0	137	431	1.466	2.714	3.954
Varmt vand	627	566	627	607	627	607	627	627	607	627	607	627
Nettab	680	614	680	658	680	658	680	680	658	680	658	680

Figur 1: Nuværende fordeling af varmeproduktion.

Nedenstående tabeller indeholder forudsætninger vedrørende nuværende produktionsenheder.

Gasmotorer	**Værdi**
Motoranlæg	4 stk. Caterpillar
Eleffekt	4 x 870, i alt 3.480 kW
Elvirkningsgrad (årsnytte)	33,24 % (nominelt 35,15 %, egetforbrug andrager 5,8 % af elproduktion jvf. DFVs opgørelse til Energistyrelsen)
Varmevirkningsgrad (årsnytte)	58,57 % (baseret på DFVs opgørelse til Energistyrelsen)
Brændsel, brændværdi	Naturgas, 39,6 GJ per ton
Udetider	8 dage årligt per motor, forskudt i perioden januar til april.
D&V	DKK 80 per MWh-el

Spidslastkedler	**Værdi**
Varmeeffekt	15,1 MW
Virkningsgrad (årsnytte)	93,0 %
Brændsel, brændværdi	Rapsolie, 36,5 GJ per ton
D&V	DKK 5 per MWh-varme

Varmelager	**Værdi**
Volumen	500 m3[1]
Temperaturdifference	40 °C
Udnyttelsesgrad	90 %
Kapacitet	20,9 MWh

1.3 Brændselspriser

"Rapsolie"-prisen er aktuelt DKK 2.500 per ton, antages konstant i faste priser over planperioden.

DFV har leveringsaftale med DONG. I beregningen anvendes en naturgaspris inkl. distributionsafgift i 2006 på 2,66 DKK/m3[2]. Denne pris er 7 % under DONGs aktuelle listepris inkl. distributionsafgift, der aktuelt udgør 2,836 DKK/m3 (september 2006), hvoraf distributionsafgiften udgør 0,219 DKK/m3[3]. Listeprisen viser en stigende tendens (Figur 2). Fremtidens naturgaspris er i væsentlig grad af betydning for rentabiliteten af investeringer, der øver indflydelse på forbruget af naturgas. Energistyrelsens seneste brændselsprisprognose fremgår af Figur 3.

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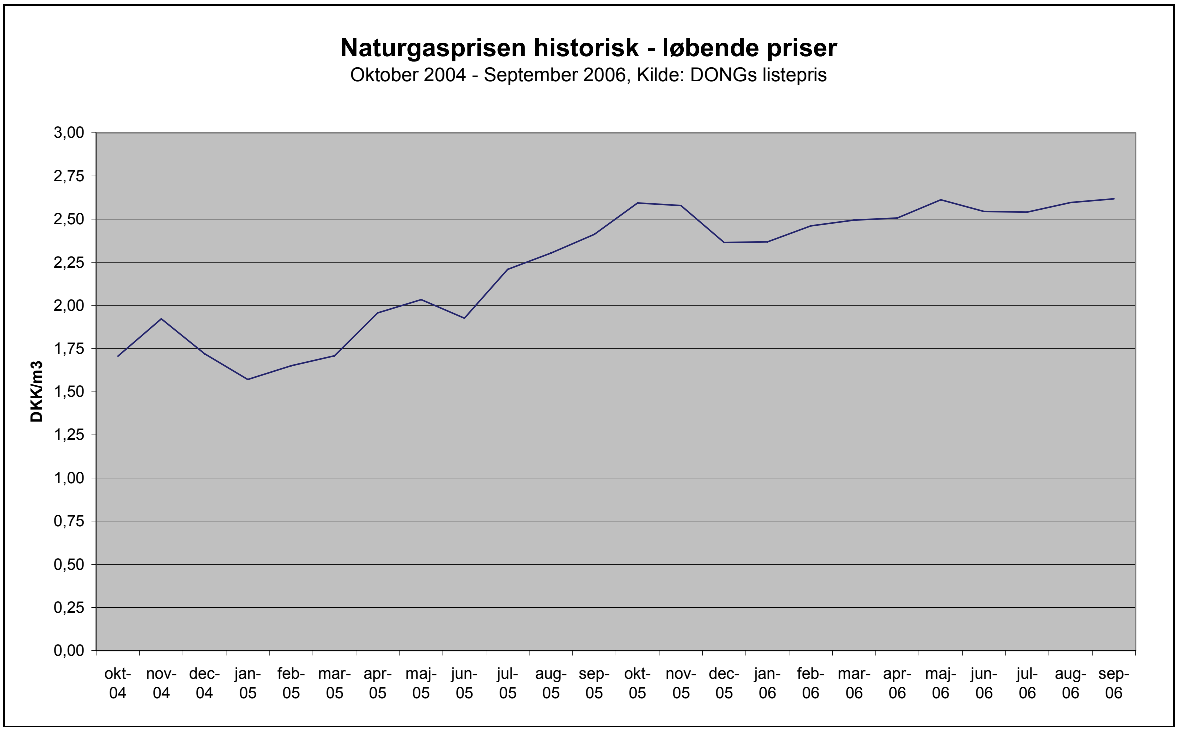
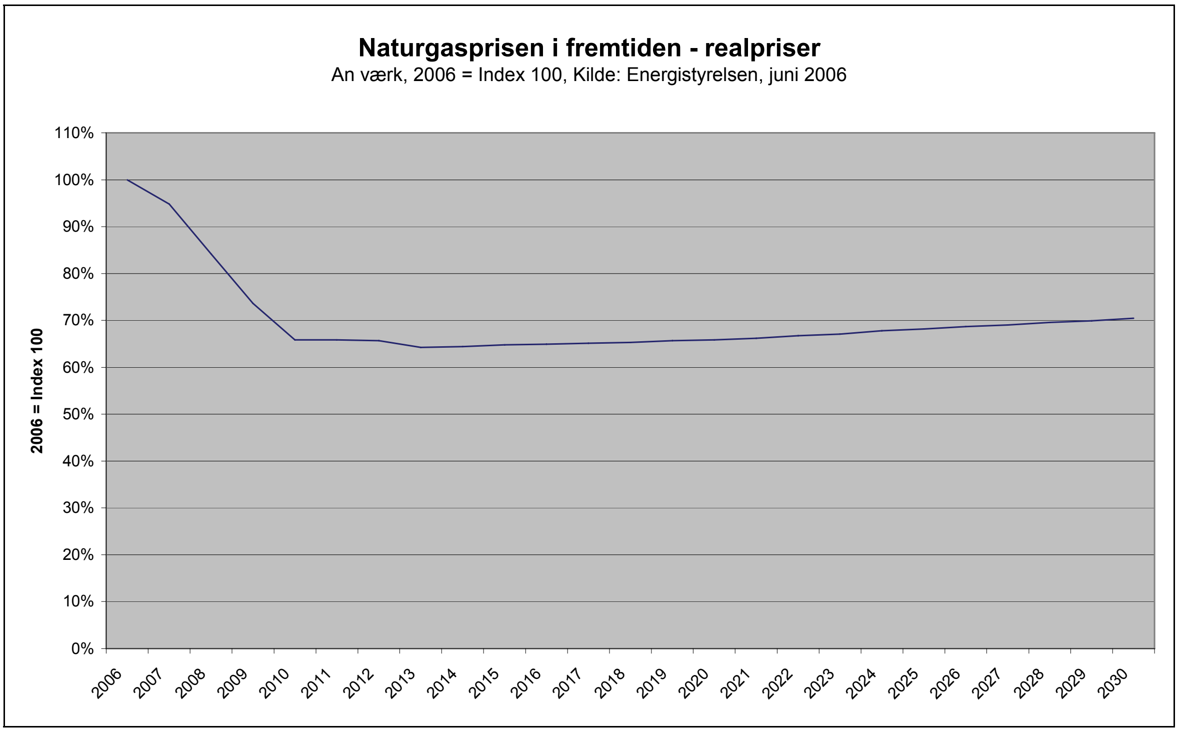
[1] Nominelt 865 m3, men analyser i EnergyPRO indikerer at varmelagret ikke fungerer optimalt. Den forventede/målte driftskarakteristik opnås ved anvendelse af et volumen på 500 m3.

[2] Antaget at være inkl. distributionsafgift.

[3] For et aftag på mellem 300.000 og 10 mio. m3 p.a.

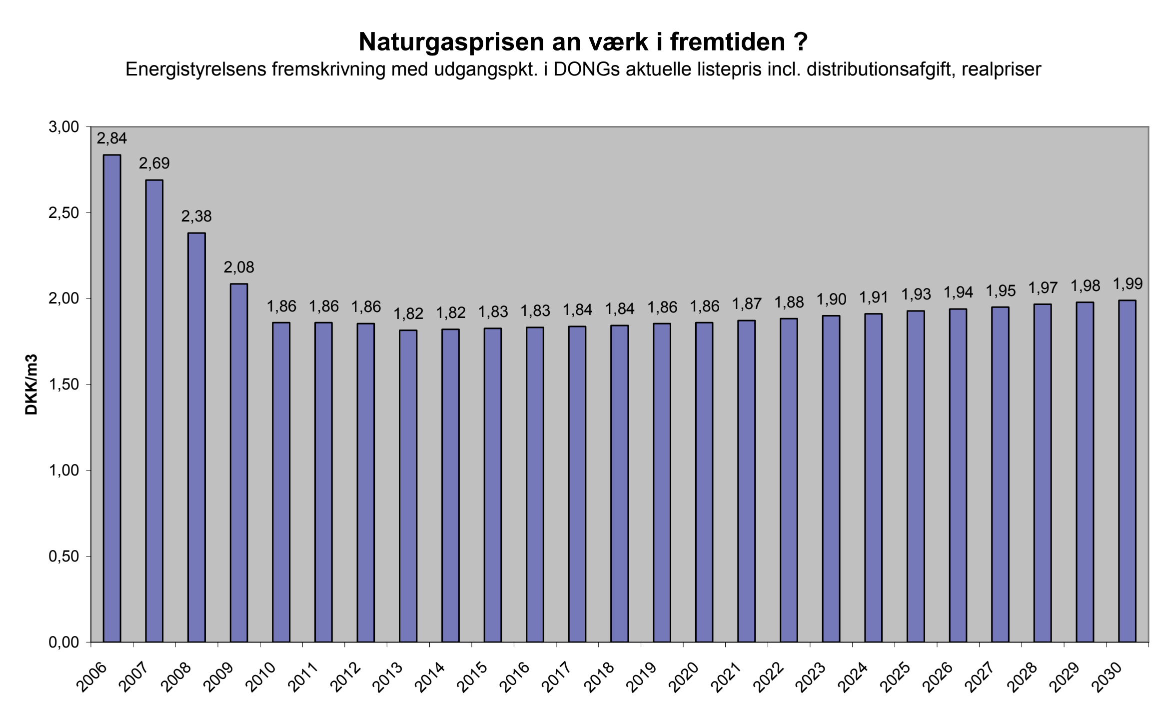


Figur 2: DONG listepris for naturgas, historisk.



Figur 3: Energistyrelsens fremskrivning af naturgasprisen, realt, indekseret..

For så vidt Energistyrelsens fremskrivning er realistisk og vil blive afspejlet i listeprisen hos DONG, svarer det til at naturgasprisen falder fra det aktuelle niveau på DKK 2,84 per m3 til DKK 1,86 per m3 i 2010 (Figur 4).



Figur 4: Fremskrivning af listeprisen baseret på Energistyrelsens fremskrivning af naturgasprisen.

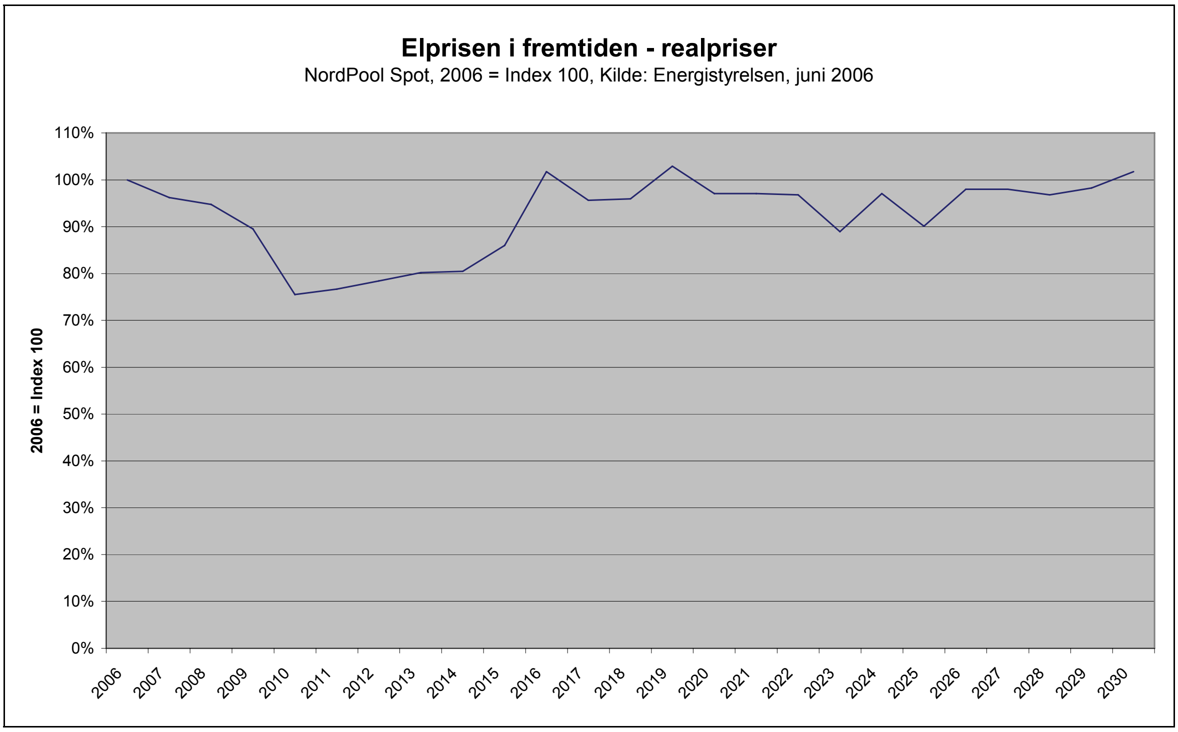
1.4 Elafregning

DFV afregner efter tre-ledstariffen, gammel aftale. Tre-ledstariffen må forventes oppebåret foreløbigt, måske frem til 2019, parallelt med aktuelle garantier for ydelse af individuelt pristillæg.

Periode	**Lavlast**	**Højlast**	**Spidslast**
November til februar	21:00 – 06:30	06:30 – 07:30 12:00 – 17:00 18:30 – 21:00	07:30 – 12:00 17:00 – 18:30
Marts til oktober	21:00 – 06:30	06:30 – 07:30 12:00 – 21:00	07:30 – 12:00
Elafregningspris (DKK per kWh)	**0,783**	**0,430**	**0,168**

DFV modtager desuden et elproduktionstilskud på 8 øre pr. kWh, dog højst DKK 640,000 p.a., der antages oppebåret. Der er ingen sikkerhed for elproduktionstilskuddets fremtidige oppebærelse.

Alternativet til tre-ledstariffen er markedsvilkår med pristillæg. Det forhold, at der er tale om elafregning efter gammel aftale, samt med henvisning til Energistyrelsens forventninger til fremtidens el-spotmarked (Figur 5), gør, at der på kort sigt må formodes ikke at være grundlag for overgang til afregning på markedsvilkår, hvilket dog kræver detaljerede driftsøkonomiske analyser for at kunne underbygge.



Figur 5: Energistyrelsens fremskrivning af elspot, realt, indekseret.

1.5 Energi- og miljøafgifter

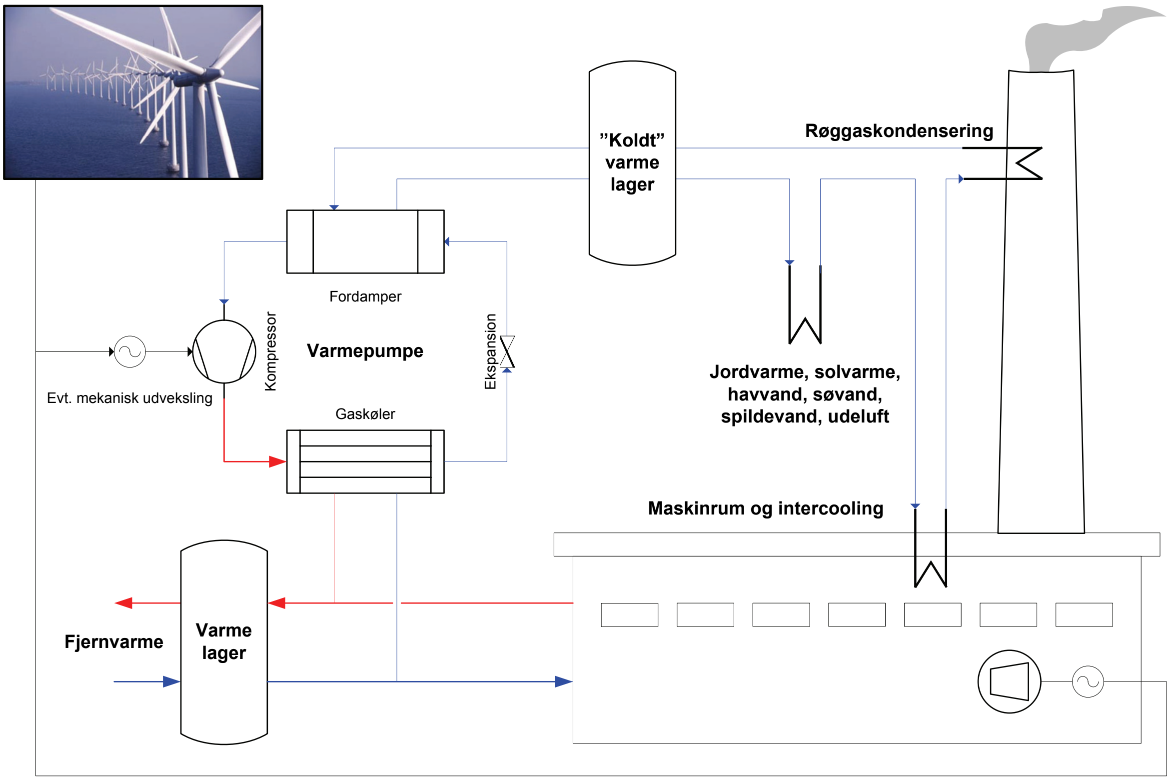
Energiafgift på naturgasanvendelse til varmeproduktion er DKK 2,042 per Nm3 naturgas, konstant i faste priser.

CO2-afgift på naturgasanvendelse til varmeproduktion er DKK 0,198 per Nm3 naturgas, konstant i faste priser.

Varmevirkningsgrad-metoden (V-formlen) anvendes ved fordeling mellem el- og varmeproduktion med en værdi på 1,25.

2. Kraftvarmepumpe-konceptet

Kraftvarmepumpe-konceptet går i korte træk ud på at udnytte røggassen fra gasmotorerne ved kondensering fra 60 °C til 30 °C som lavtemperaturkilde i en højeffektiv transkritisk varmepumpe, der anvender CO2 som kølemiddel under højt tryk. Anden lavtemperaturkilde kan også indgå.



Figur 6: "Kraftvarmepumpe"-konceptet. Det "kolde" varmelager og dermed muligheden for forskudt produktion på eldreven varmepumpe indgår ikke i nærværende analyse. Der antages i nærværende analyse alene samtidig drift af varmepumpe og gasmotorer, samt mekanisk, omend kapacitetsreguleret udveksling herimellem.

En væsentlig konsekvens af kraftvarmepumpekonceptet er en bedre udnyttelse af naturgassens energiindhold, for DFVs vedkommende øges kraftvarmeenhedens totalvirkningsgrad i den konkrete drift fra 91,81 % til 96,84 %, baseret på nedre brændværdi. Teoretisk set kan der opnås højere virkningsgrader, hvilket formodes at kunne opnås ved at reducere bindingen til varmebehovet.

Idet der aktuelt ikke er skatteteknisk basis for at anvende egenproduceret elektricitet til at drive en fjernvarmeproducerende varmepumpe, anvendes forudsætninger for en hydraulisk udveksling mellem gasmotorer og varmepumpe, der sammen med mekanisk kapacitetsregulering 25 - 100 %[4] betyder, at varmepumpen drives, når mindst en gasmotor er i drift.

Kraftvarmepumpe 1 MW-varme	**Anslået anlægsomkostning (DKK)**
Varmepumpe samlet	3.000.000
Mekanisk kapacitetsregulering 25-100 %	100.000
Udskiftning af skorstenskerne	500.000
Fælles ny LT veksler[5]	700.000
Samlet anlægsudgift	**4.300.000**
Samlet anlægsudgift per MW-el	16.700.000

Antaget levetid på investering er 20 år. D&V omkostninger antages at stige til DKK 90 per MWh netto-elproduktion.

I et mere avanceret koncept skal varmepumpen kunne drives elektrisk af gasmotorer kombineret med mulighed for køb af el fra elnettet, herunder indkøring på balancemarkedet. Dette koncept vil kunne øge DFVs robusthed overfor kortsigtede forandringer i el- og gasmarkedet.

Et mere avanceret koncept kræver fuldt udbygget adgang til en lavtemperatur varmekilde, der er tilgængelig selvom gasmotorerne ikke er i drift. Dette kunne opnås ved lagring af røggasvarme eller/og ved etablering af jordvarmeanlæg. Et jordvarmeoptag af den udlagte størrelse vil anslået nå et samlet omfang på 23 km, og koste DKK 1,2 mio. at etablere.[6] En lagertank til røggasvarme på 535 m3 ville fuldt lagret muliggøre drift af varmepumpe i 24 timer uden samtidig kraftvarmeproduktion, og kan anlægges for DKK 400.000.[7]

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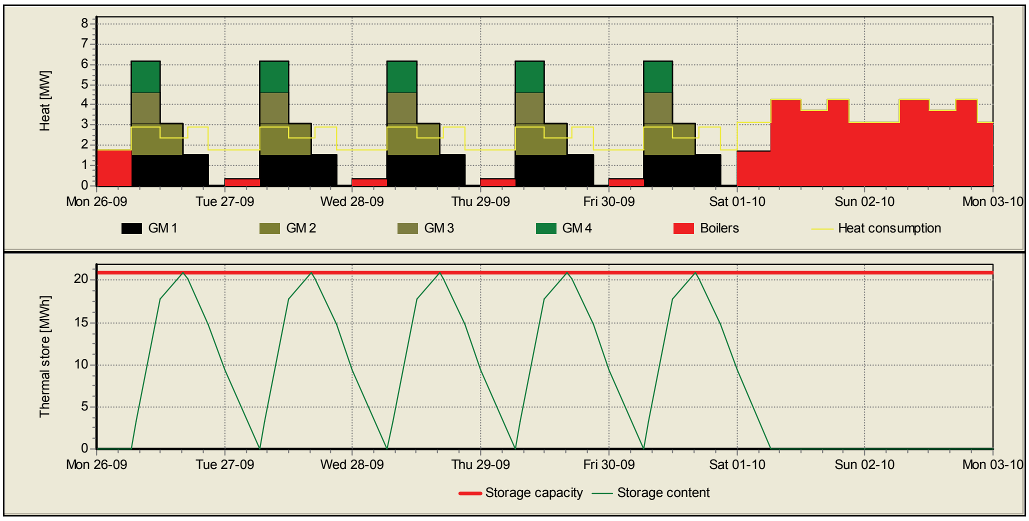
[4] Ved koblingsarrangement eller overstrømningsventiler.
[5] Anslået DKK 500.000-700.000.
[6] Dimensionerende varmeoptag på 698 kW, 30 W/m, DKK 50 per m. Svarer i øvrigt til DKK 5 mio. per MW-el. Ekskl. evt. arealbehov. Hvad er arealbehovet for et sådant anlæg?
[7] Temperaturdifference 30°C (30°C-60°C), lagringskapacitet 16,7 MWh ved udnyttelsesgrad på 90 %, DKK 750 per m3. Svarer i øvrigt til DKK 1,5 mio. per MWe. Ekskl. evt. arealbehov.

3. Teknisk-økonomiske analyseresultater

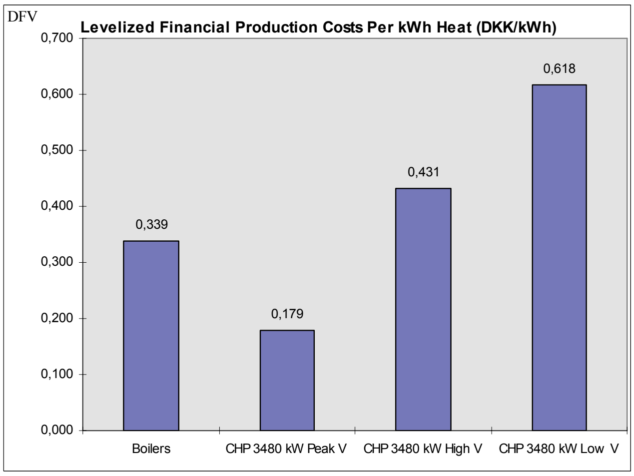
3.1 Nuværende drift med ”beregnet varmelager”

Figur 7 viser aktuel uges driftsprofil for værk med beregnet varmelager (se fodnote 1).



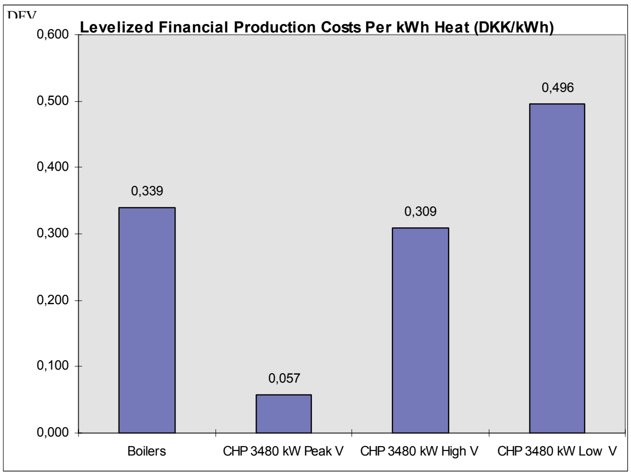
Figur 7: Driftsprofil (varmeproduktion og varmelager) for uge 39 med 500 m3 varmelager.

Figur 8 viser de beregnede balancerede varmeproduktionspriser for forskellige produktionsenheder, når naturgasprisen antages at være konstant i faste priser. Det fremgår, at produktionsprisen på spidslastkedlerne i dette scenarium ligger godt 20 % under produktionsprisen på gasmotorerne i højlast. Dette afspejler den aktuelle omkostningssituation og indikerer at der vil være en driftsøkonomisk besparelse i at overgå til kedeldrift i højlastperioder, for så vidt det er forsvarligt i praksis.



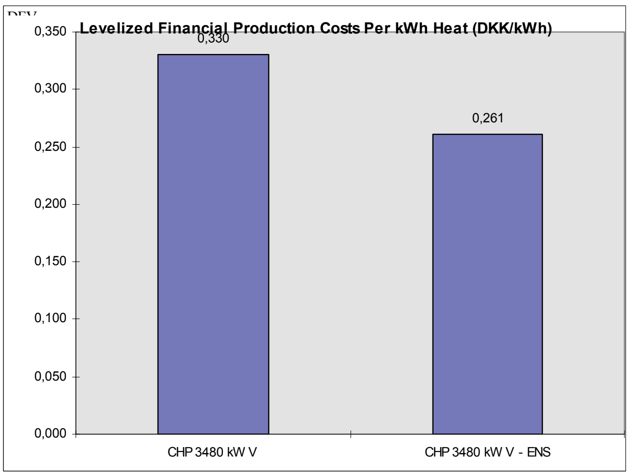
Figur 8: Balancerede varmeproduktionspriser for produktionsenheder i afregningsperioder. Naturgasprisen antages konstant i faste priser.

Figur 9 viser de balancerede varmeproduktionspriser for forskellige produktionsenheder, når naturgasprisen antages at følge Energistyrelsens fremskrivning. Det fremgår, at produktionsprisen på spidslastkedlerne i dette scenarium er godt 10 % dyrere i drift end gasmotorerne i højlast. Med Energistyrelsens aktuelle forventning til fremtidens naturgaspriser vil der på længere sigt således ikke være basis for at omlægge til kedeldrift i højlast.



Figur 9: Balancerede varmeproduktionspriser hvor for produktionsenheder i afregningsperioder. Naturgasprisen antages at følge Energistyrelsens fremskrivning.

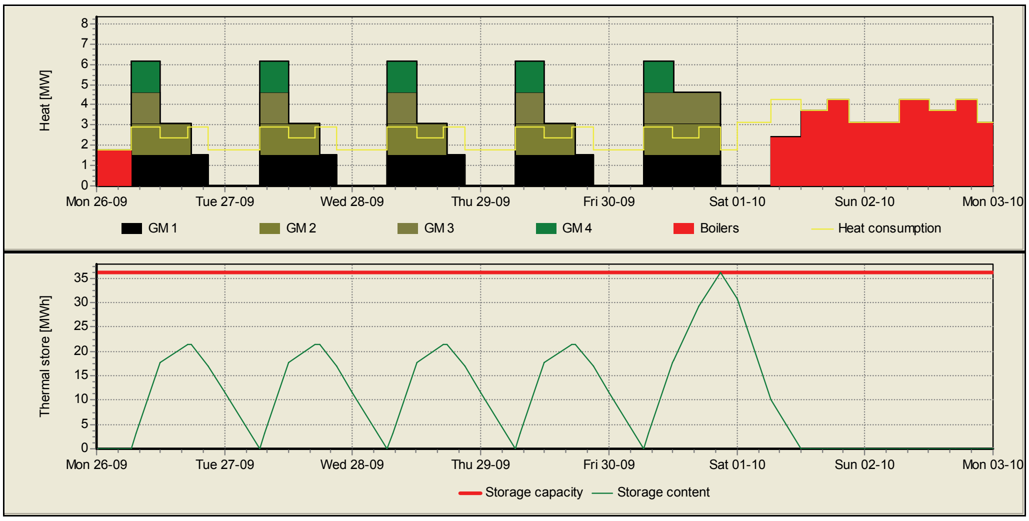
Figur 10 viser den samlede balancerede varmeproduktionspris for DFV under den nuværende driftsstrategi, hvor gasmotorer drives i spids- og højlast, under antagelse af at naturgasprisen dels er realt konstant, dels vil følge Energistyrelsens fremskrivning. Det fremgår, at varmeproduktionsprisen er godt 20 % lavere i Energistyrelsens prisscenarium.



Figur 10: Balanceret varmeproduktionspris med naturgaspris baseret på hhv. konstant realprisniveau og Energistyrelsens fremskrivning.

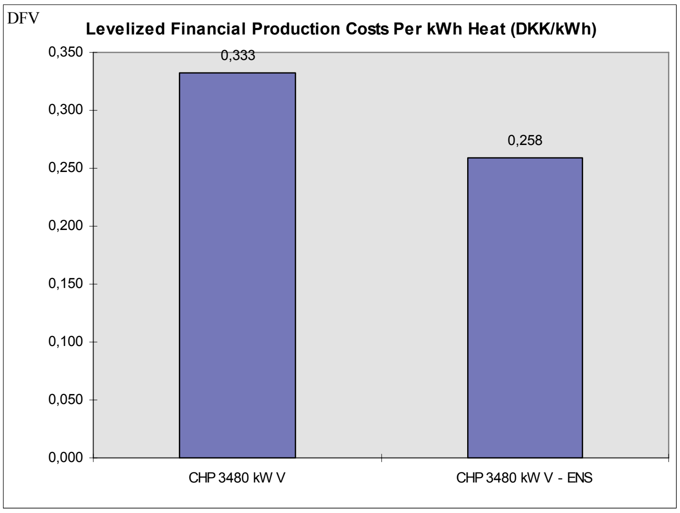
3.2 Nuværende drift med "nominelt varmelager"

Figur 11 viser aktuel driftsprofil for værk med nominelt varmelager, dvs. hvor driften indrettes efter at der reelt er tale om en lagervolumen på 865 m3. Ved sammenligning med Figur 7 ses at dette giver anledning til øget gasmotordrift i højlast.



Figur 11: Driftsprofil (varmeproduktion og varmelager) for uge 39 med 865 m3 varmelager.

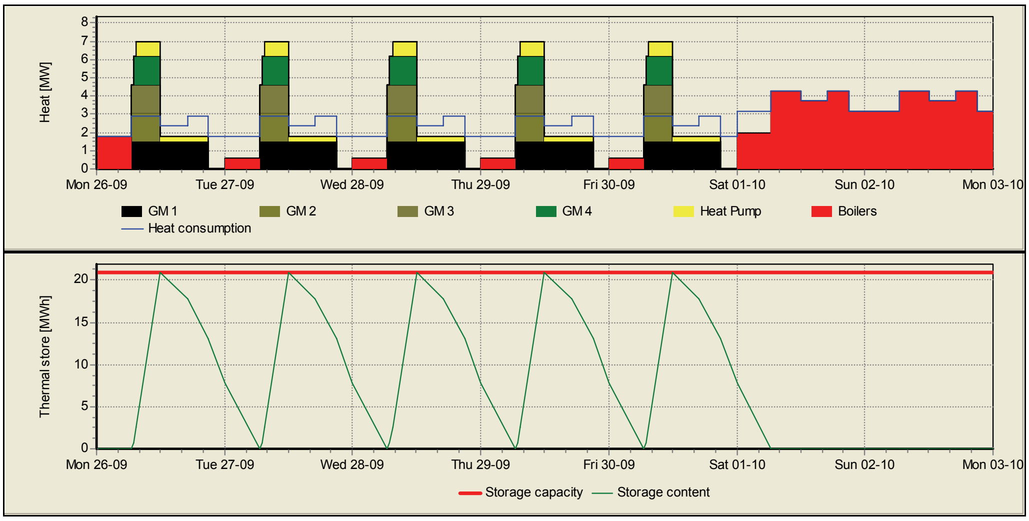
Figur 12 viser ved sammenligning med Figur 10, at en driftsstrategi med nominelt varmelager ikke giver en driftsøkonomisk besparelse ved konstant 2006-prisniveau for naturgas. Dette skyldes den lavere produktionspris ved kedeldrift i højlast, der fortrænges. Antages Energistyrelsens fremskrivning at gælde opnås en driftsøkonomisk besparelse på 2 %, hvilket skyldes øget elproduktion i højlast.



Figur 12: Balanceret varmeproduktionspris ved nominelt varmelager, hhv. konstant realprisniveau og Energistyrelsens prisfremskrivning for naturgas.

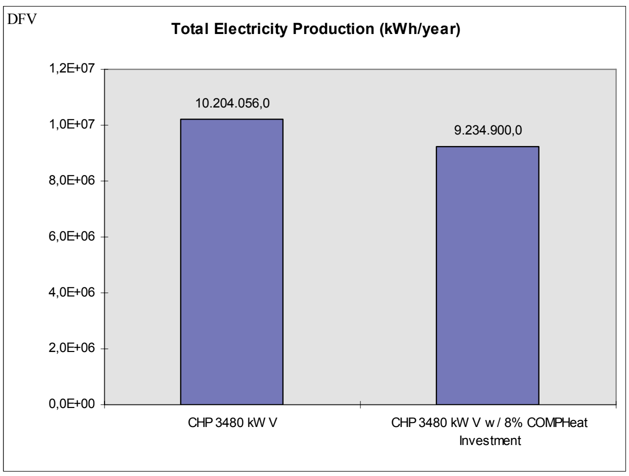
3.3 Drift med ”kraftvarmepumpe” og beregnet varmelager

Figur 13 viser aktuel driftsprofil for værk med ”kraftvarmepumpe” og beregnet varmelager. Sammenlignes med Figur 7 ses, at varmepumpen typisk fortrænger gasmotordrift i højlast. Med denne driftsprofil reduceres spidslastkedlernes andel af varmeproduktionen på årsbasis fra 53,4 % til 50,4 %. Gasmotordrift i højlast reduceres fra 1.698 til 1.569 fuldlasttimer. Gasmotordrift i spidslast er uændret.



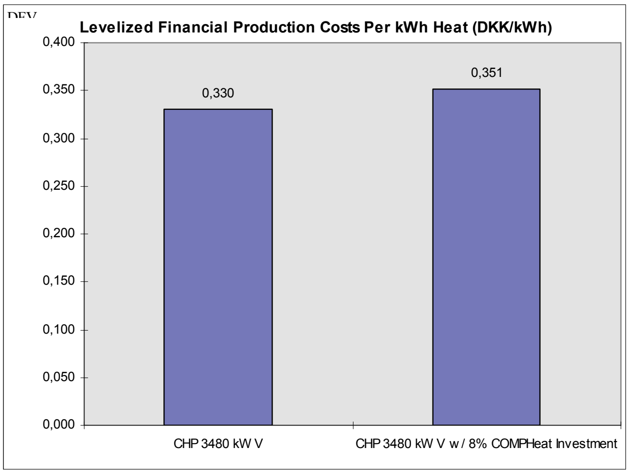
Figur 13: Driftsprofil for “kraftvarmepumpe” (varmeproduktion og varmelager) for uge 39 med 500 m3 varmelager

Figur 14 viser den årlige netto-elproduktion for ”kraftvarmepumpe” sammenlignet med nuværende anlæg og drift. Det fremgår, at netto-elproduktionen reduceres med 10%. Reduktionen skyldes dels at elproduktionen ved gasmotordrift reduceres med varmepumpens effektforbrug samtidig med at den øgede varmeproduktion helt fortrænger gasmotordrift i visse højlasttimer.



Figur 14: Årlig netto-elproduktion for reference og “kraftvarmepumpe”.

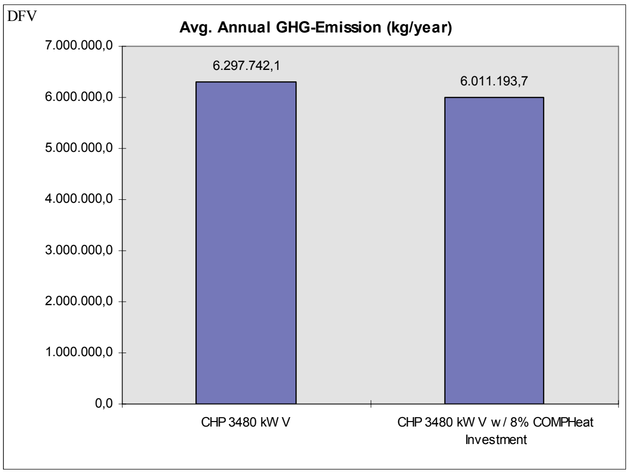
Figur 15 viser den samlede balancerede varmeproduktionspris for ”kraftvarmepumpe” sammenlignet med nuværende anlæg og drift. Det fremgår, at varmeproduktionsprisen øges med 6 % ved installation af varmepumpe under forudsætning af konstant 2006-prisniveau for naturgas. Stigningen er på 9 % under forudsætning af Energistyrelsens prisfremskrivning for naturgas.



Figur 15: Balanceret varmeproduktionspris for reference og “kraftvarmepumpe”.

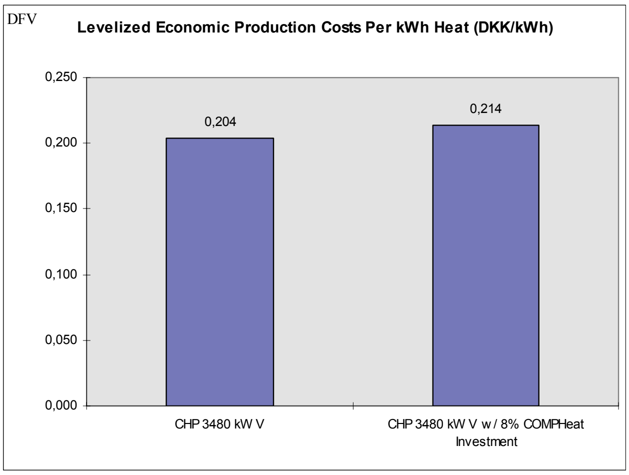
3.4 Miljø, samfundsøkonomi, statsfinanser – argumenter til den energipolitiske debat

Figur 16 viser den årlige emission af CO2-ækvivalenter under forudsætning af at den ekstra elproduktion som leveres af elsystemet produceres under CO2-kvotesystemet.



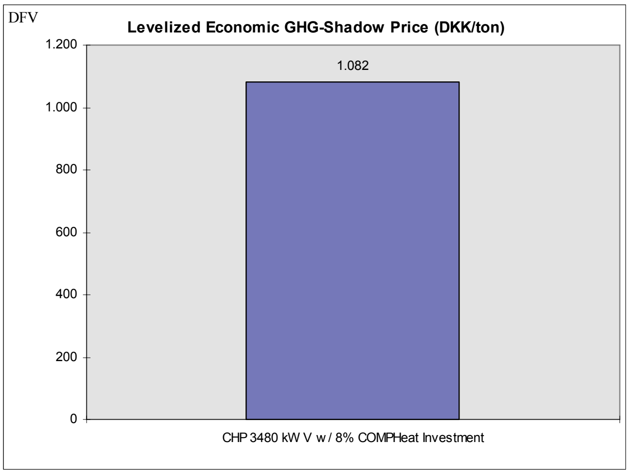
Figur 16: Årlig CO2-emission for reference og “kraftvarmepumpe” når der ses bort fra systemforskydninger som følge af reduceret elproduktion.

Figur 17 viser, at den balancerede samfundsøkonomiske varmeproduktionspris øges med 5 % for ”kraftvarmepumpen”.



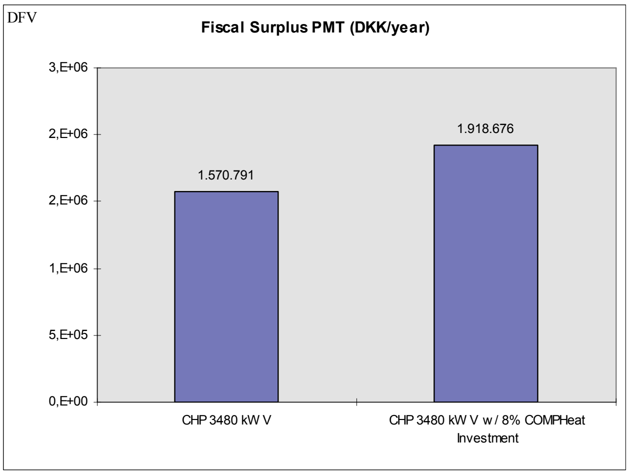
Figur 17: Balanceret samfundsøkonomisk varmeproduktionspris for reference og “kraftvarmepumpe” ekskl. værdi af eksternaliteter, herunder evt. CO2-fortrængning.

Figur 17 viser, at CO2-skyggeprisen for ”kraftvarmepumpen” beløber sig til DKK 1,082 per ton CO2, hvilket er væsentlig over den aktuelle og forventede fremtidige markedspris for CO2-kvoter. Dette resultat forudsætter at den reducerede elproduktion opvejes af anlæg indenfor CO2-kvotesystemet.



Figur 18: Balanceret samfundsøkonomisk varmeproduktionspris for reference og “kraftvarmepumpe” ekskl. værdi af eksternaliteter, herunder evt. CO2-fortrængning.

Figur 17 viser, at ”kraftvarmepumpen” giver et årligt statsfinansielt overskud på DKK 350,000, bl.a. under forudsætning at afgiftsniveauet holdes konstant i faste priser, samt at investeringer og evt. øgede D&V-udgifter skaber mer-beskæftigelse.



Figur 19: Årlig statsfinansielt overskud for reference og “kraftvarmepumpe”.

4. Avancerede alternativer

Dette notat har valgt alene at se mere detaljeret på den enkleste og mest driftssikre strategi for integration af varmepumpe i eksisterende kraftvarmeproduktion. Det kan dog ikke afvises at der fra et selskabsøkonomisk perspektiv og fra et samfundsøkonomisk systemperspektiv kan være alternative driftsstrategier, der er ønskelige. Nedenfor følger en kort oversigt over og diskussion af avancerede alternativer:

Løsninger		**Diskussion**
A	Kraftvarmepumpe (fuld røggasudnyttelse). Alene mekanisk integration, samtidig drift af varmepumpe og kraftvarmeenhed. Uden koldt varmelager.	Kompliceret kobling mellem CHP og HP. Tab af kraft ved drift, slitage, højere D&V, besværet afkobling af varmepumpe, når fuld kraftproduktionskapacitet ønskes. Driftsikker, men uden energisystemreguleringseffekt.
B	Kraftvarmepumpe med mulighed for forskudt produktion under L1417, derfor lagring af røggasvarme i koldt varmelager. Elektrisk udveksling, evt. kombineret med mekanisk udveksling.	Enkel kobling mellem CHP og HP. Kræver en mere avanceret styringsstrategi. Overkommelig investering i koldt varmelager. Driftsikker, og med betydelig energisystemreguleringseffekt.
C	*Som ovenstående, dertil jordslangeanlæg.*	*Vil være konkurrencedygtig overfor kedler i alle spotprisperioder, men har ikke tilstrækkelig kapacitet til helt at fortrænge kedelproduktion. Vil fortrænge 30 % af den eksisterende varmeproduktion på spidslastkedler. Økonomisk tvivlsom især pga. af udgifter til jordslangeanlæg.*
D	*Som ovenstående, men med fuld varmeproduktionskapacitet og jordslangeanlæg.*	*Kan ses som et alternativ til fortsat kraftvarmeproduktion. Alene jordslangeanlægget vil koste DKK 5 mio, samlet anlægspris næppe under DKK 20 mio. Stor økonomisk risiko, hvor driftsøkonomien vil være helt afhængig af elprisudviklingen. Kan være interessant i et samfundsøkonomisk systemperspektiv under forceret vindkraftudbygning, hvor spotmarkedet må forventes at udvise store udsving. Kan evt. kombineres med sæsonlagring af varme.*

[kolofon

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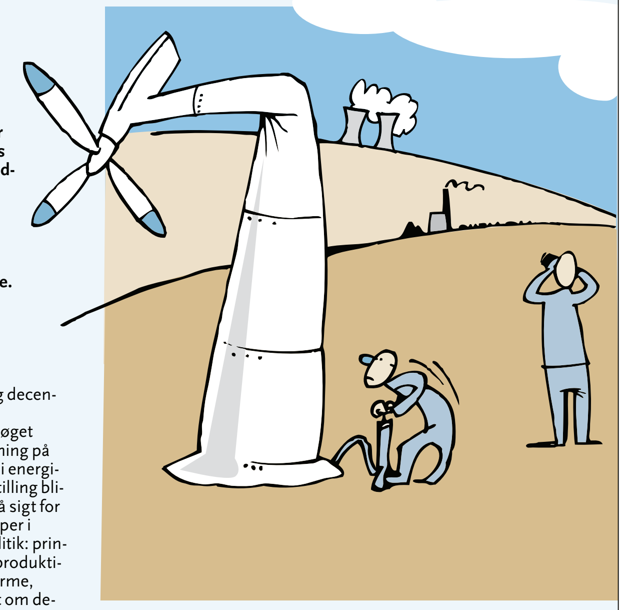
KRONIK Energipolitik

Lad os fremtidssikre den decentrale kraftvarme

Af Morten Boje Blarke
Civ.ing., ph.d.-stipendiat inden for større varmepumpeanlægs rolle i et robust el-system, Aalborg Universitet.



Det en misforstået varetagelse af samfundets interesser, når regering og opposition har spændt udviklingen af fremtidens bæredygtige energisystem for den hest, der kræver mere vindkraft i Danmark her og nu. De store aktører vil nemlig sørge for bedst muligt samspil mellem vindmøllerne og den centrale elproduktion udenom de decentrale kraftvarme-producenter, og samtidig vil mere vindkraft presse priserne på spotmarkedet for el yderligere, hvilket kan få de decentrale producenter til helt at opgive at samproducere kraft og varme.

At det vil gå sådan, bygger jeg på tanker om to sammenhængende fremtidsspor, der ser ud til at kunne gøre sig gældende på kort sigt:

Scenarium 1: Vindkraftudbygningen vil snart afføde krav om nye elforbindelser til udlandet. Dette vil åbne op for øget eksport og import af el også fra centrale kraftværker, herunder indenlandsk kulkraft og udenlandsk kernekraft. Dette vil sammen med vindkraftens indflydelse på elmarkedet i stigende grad presse priserne i det danske spotmarked under smertegrænsen for de decentrale kraftvarmeproducenter, der vil ty til elkedler, i bedste fald til varmepumper, eller anden kedelproduktion i varmeproduktionen, i stedet for kraftvarmeenheder.

Vindkraft nu giver centralisering

Der er aktører, der vil have interesse i længere perioder med sådanne tilstande, da det kan resultere i øgede markedsandele, endog delvist monopolisere det danske elmarked.

I værste fald vil længere perioder med svigtende spotpriser få eksisterende decentrale producenter til helt at opgive kraftvarmeproduktionen. Dermed har vi en situation hvor mere vindkraft her og nu ender med at undergrave et væsentligt princip i dansk energipolitik; princippet om samproduktion af kraft og varme.

Scenarium 2: Vindkraftudbygningen vil være baseret på en elforbrugerfinansieret ejerskabsmodel, der støtter de store aktører i energibranchen. Da de store aktører nu både skal eje vindmølleparker og centrale kraftværker, kan man ikke fortænke dem i at ville være interesserede i at skabe samspil mellem vindkraft og central elproduktion, uden om de decentrale værker.

> *“Man kan ikke fortænke de store aktører i at ville være interesserede i at skabe samspil mellem vindkraft og central elproduktion, uden om de decentrale værker.*

Husholdninger, kommuner, og fremstillingsvirksomheder ejer de decentrale værker, men det bliver ikke en eneste dansk husholdning eller kommune beskåret at købe andele i fremtidens store hav- eller landbaserede vindmølleparker. Havde de haft andel i vindkraftudbygningen, måtte de kunne forventes at søge et samspil mellem vindkraft, decentral kraftvarmeproduktion, og slutforbrug, uden om de centrale værker. Dermed har vi en situation hvor mere vindkraft kan ende med at undergrave et energisystem, der baserer sig på et samspil mellem vindkraft og decentral kraftvarme.

Kort sagt kan øget vindkraftudbygning på dette tidspunkt i energisystemets omstilling blive et problem på sigt for centrale principper i dansk energipolitik: princippet om samproduktion af kraft og varme, samt princippet om decentrale ejerskaber.
Hvem har interesse i det?
Man skal ikke være blind for, at det er der aktører, der har. Men danske politikere burde ikke have det.

Drop de centrale producenter

Hvad bør der gøres for at undvige dette foruroligende udviklingsspor, der så åbenlyst strider mod intentioner i dansk energipolitik og EU's kraftvarmedirektiv?

Jeg mener, at målet for Danmark bør være et energisystem helt uden centrale kraftproducenter, altså et energisystem, der baserer sig på et samspil mellem vindkraft, decentral kraftvarme, og slutforbrug.

> *“Det er regeringens ansvar, at dens energipolitiske genfødsel sikrer befolkningens langsigtede interesser, ikke populære interesser, endsige dominante aktørers økonomiske interesser.*

Kan det lade sig gøre? Det burde det i princippet kunne, endog med økonomisk og miljømæssig fordel, men det kræver politisk enighed om virkemidler, der dyrker decentrale ejerskabsmodeller, både i kraftproduktionen og i vindkraftudbygningen.

Teknisk set handler det om bedre koordinering mellem vindkraft, decentrale kraftvarmeproducenter, og slutforbrugere, herunder indpasning af ny teknologi, først i form af varmepumper og varmelagre, siden fleksibelt slutforbrug, integreret produktion af flydende brændsler, ellagring, og anden tilsvarende funktionalitet.

Varmepumper giver fleksibilitet

Varmepumper er her ikke en exit-strategi som i Scenarium 1, men en driftsstrategisk option, der skaber fleksibilitet samtidig med at princippet om samproduktion bevares. Det er her i fremtidssikringen af de decentrale kraftvarmeproducenters omstilling til vind-venlig produktion, der er brug for nye effektive virkemidler lige nu – ikke på vindkraftområdet.

Jeg har tidligere fremlagt forslag om, at der bør gives adgang til godtgørelse af afgift af op til ti pct. af egenproduceret elektricitet anvendt i varmepumper til fremstilling af fjernvarme. Dertil vil det, ikke mindst i lyset af kraftvarmedirektivet, være et godt tidspunkt at få ryddet op i de to modeller for kraft-varme-beskatning af gasforbruget til varmeproduktion. En bedre model ville være at beregne gasforbruget alene på grundlag af varmeproduktionen med en beregningsfaktor på 1,33 for kraftvarmeanlæg uden varmepumpe og en beregningsfaktor på 1,66 for kraftvarmeanlæg med varmepumpe.

Første generation af Danmarks bæredygtige energisystem er skabt på basis af lokale løsninger – på forsyningssiden med vægt på udbygning med vindkraft og kraftvarme. Anden generation af det bæredygtige energisystem reducerer yderligere behovet for centrale værker og skal skabes ved investeringer i fleksibilitet med udgangspunkt i principper om samproduktion og decentrale ejerskaber.

Befolkningens langsigtede interesser

Det bliver billigere, det bliver renere, og det vil give mulighed for en mere retfærdig fordeling af energisektorens værditilvækst, formentlig på bekostning af store kapitalfonde. Det er selvsagt regeringens ansvar at dens energipolitiske genfødsel sikrer befolkningens langsigtede interesser, ikke populære interesser, endsige dominante aktørers økonomiske interesser.

Dette kræver stramme tøjler på det globale plan, virkemidler der sikrer at vindkraftudbygningen sker i en balancegang med videreudvikling af andre decentrale produktionsformer, herover en regulær liberal satsning på lokale operatører og lokale løsninger. □

En lille justering af afgiftsreglerne kunne blive et gennembrud for de store varmepumper, mere effektiv kraftvarmeproduktion, og indregulering af vindkraft

Morten Boje Blarke, Civilingeniør, Ph.D. stipendiat indenfor større varmepumpeanlægs rolle i et robust el-system, finansieret af Energinet.dk og Aalborg Universitet

I debatten om store varmepumpers mulige rolle i fremtidens energisystem, ønsker jeg at rette opmærksomheden mod et sikkert velkendt forhold i afgiftspolitikken, som jeg finder perverst (ordet anvendt strengt videnskabeligt om utilsigtede effekter), og som jeg hermed fremlægger forslag til at få lavet om på. Min hypotese er, at får vi lavet om på dette ene forhold, vil de store varmepumper, og dermed bidraget herfra til indregulering af vind, hurtigt komme med. Samtidig kan vi spare industrien og fjernvarmeproducenterne for unødigt besvær med hydraulik og elpatroner.

Baggrunden er, at Landsskatterettens afgørelse i oktober 2003 i sagen om Augustenborg Fjernvarme førte til en lovpræcisering, der gør det klart, at der ikke er adgang til godtgørelse af afgift af elektricitet anvendt i varmepumper til fremstilling af fjernvarme, selv for varmepumper, der indgår som en integreret del af kraftvarmeanlægget. Så længe en varmepumpe drives af elektricitet, også egenproduceret, skal der betales fuld afgift af denne elektricitet. Efter Augustenborg-sagen vedtog Folketinget L 210, hvor det præciseres at ”Af elektricitet fremstillet af varmeværket selv, der anvendes til fremstilling af varme i varmepumper i varmeværker, som leverer varme til de kollektive fjernvarmenet, betales afgift efter stk. 1.” Augustenborg vandt sagen, og fik 3,5 million kr. retur i moms og afgifter for historisk drift, på grund af en upræcis lovtekst, men det blev ikke til et løft for varmepumpeteknologien, afgørelsen blev brugt til at præcisere loven. Og Augustenborg har efterfølgende taget varmepumpen ud af drift.

Hvad betyder lovens præcisering for de løsninger, der nu tilgår markedet, der involverer store varmepumper?

Firmaer som f.eks. Advansor og Xrgi leverer varmepumpeløsninger, som elegant omgår afgiftsloven. Disse anlæg kombinerer kraftvarmeenhed og varmepumpe, og repræsenterer verdens hidtil mest effektive kraftvarmeanlægsteknologi med en total virkningsgrad på 105 % målt på nedre brændværdi. Den høje virkningsgrad opnås ved røggaskondensering og intercooling. Det elegante og fuldt lovlige består i at der ikke er tale om en eldreven varmepumpe, men om en varmepumpe, der drives af et hydraulisk system, der optager effekt fra gasmotorens drivaksel.

Dette er perverst: Disse anlæg fungerer i princippet ligesom hvis varmepumpen havde været eldreven, altså som i Augustenborg, bortset fra en række væsentlige ulemper: De er mindre effektive pga. af tab i det hydrauliske system, de er dyrere i anlægsinvestering, de er dyrere og mere fejlbårne i drift - og de giver ikke mulighed for selvstændig drift af varmepumpe, de kan altså ikke bidrage til indregulering af vind.

Der er naturligvis stor interesse for disse meget effektive anlæg, og de fungerer i øvrigt fortrinligt, det bliver selskabsøkonomisk helt optimalt, hvis de samtidig dækker et kølebehov (tri-generation). Varmepumpen reducerer elproduktionen fra kraftvarmeenheden med omkring 10 %, men øger til gengæld varmeproduktionskapaciteten med omkring 30 %. Selskabsøkonomiske tilbagebetalingstider for værker på markedsvilkår og CO2-kvoter, er helt nede på 3-4 år. Der er selvsagt et stort simrende marked for disse anlæg.

Mit konkrete forslag er, at der hurtigst muligt gives adgang til godtgørelse af afgift af op til 10 % af egenproduceret elektricitet anvendt i varmepumper til fremstilling af fjernvarme. Dermed får vi en løsning til industri og fjernvarmeproduktion, som vi i praksis alligevel får, men el-dreven i stedet for hydraulik-dreven, og dermed med en langt bedre selskabs- og samfundsøkonomi (samme funktionsprincip, men mere effektiv, mere driftsikker, og billigere i anlægsomkostning). Samtidig får vi, som bonusløsning, mulighed for selvstændig drift af eldreven varmepumpe, og altså et bidrag til indregulering af vind.

Det skal tilføjes, at der er tale om ny varmepumpeteknologi, der kører i pilotanlæg med gode resultater, der muliggør fremløbstemperaturer over 80 grader, dvs. et temperaturniveau som fjernvarmesektoren efterspørger, og som altså også i praksis giver mulighed for selvstændig drift. For at gøre selvstændig drift af varmepumpen mulig, vil det være nødvendigt at etablere et kølebehov eller en lavtemperatur varmekilde, f.eks. jordvarme. Dette vil øge anlægsinvesteringen, men ikke nødvendigvis tilbagebetalingstiden, det kan muligheden for selvstændig drift ophæve. Det skal også bemærkes, at varmepumpens produktionskapacitet på 30 % af kraftvarmeenhedens eksisterende produktionskapacitet ikke i længden giver mulighed for 100 % selvstændig drift af varmepumpe, men kræver supplerende produktion fra gasmotor eller kedler, eller på sigt integration af solvarme og sæsonlagring af varme.

I forbindelse med debatten om Lov 81, der skal åbne op for elanvendelse i fjernvarmeproduktionen uden samtidig kraftvarmeproduktion, er det blevet fremført, at varmepumper kunne være et alternativ til elpatroner. Men faktisk viser vores analyser, at hvis et værk på markedsvilkår har valgt at investere i en varmepumpe, der muliggør drift med fuld varmeproduktionskapacitet alene med varmepumpe og akkumulatortank, altså en varmepumpe der vil være 3 gange så stor som i konceptet beskrevet ovenfor, så er varmepumpen marginalt set så relativt omkostningseffektiv, at den, selv med de gældende afgiftsregler, i praksis overtager fjernvarmeproduktionen fra kraftvarmeenheden. Varmepumper med fuld varmeproduktionskapacitet er ikke et alternativ til elpatroner, men til kraftvarmeproduktion!

Men med det ovenstående koncept, og forslaget til lovændring, vil eldrevne varmepumper, enkelt integreret med kraftvarmenhed og i anlægsstørrelser på omkring 1/3 af den eksisterende varmeproduktionskapacitet, være til fordel for både industri og samfund, og med sin oplagte hensigtsmæssighed og fleksibilitet fremstå som et ophøjet alternativ til planer om etablering af elpatron.

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Abstract

This thesis investigates options for handling the problem of intermittency related to large-scale penetration of wind power into the West Danish energy system. But rather than being a story about wind power, the thesis explores the principles by which distributed energy plants could be better designed and operated to provide energy system services, supporting intermittent supply, while reducing the need for central power plants and cross-national transmission capacities.

In essence, the thesis assesses the consequences of integrating large-scale heat pumps with distributed cogenerators in favour of a domestic integration strategy for handling intermittency towards a sustainable energy system.

It is found that large-scale transcritical compression heat pumps are suitable and ready for integration with existing cogenerators, but that system-wide energy, environmental, and economic benefits are very sensitive to actual concepts of integration. The innovative CHP-HP-CS concept that relies on heat recovered from cooling and condensation of flue gasses, adds, in addition to a heat pump, a cold storage for storing recovered heat, which allows for independent operation of cogenerator and heat pump. While this concept results in increasing a typical plant's fuel efficiency from 92 % to 97 %, the plant's reduced electricity production results in plant-related system-wide CO2 emissions increasing by as much as 20 %. The increase in CO2 emissions is minimized by disallowing concurrent operation of cogenerator unit and heat pump unit. The CHP-HP-GS concept that relies on unconstrained heat recovered from ground sources offers a 10 % reduction in the plant's system-wide CO2 emissions when disallowing concurrent operation.

The thesis shows that concepts for integrating heat pumps with cogenerators comes with significant variations in boiler operation and cogeneration being substituted, with the heat pump entering as an intermediate-load heat production unit with full-load hours as few as 1350 hours according to concept, and that the resulting overall economic costs of heat production typically increase by 2 % to 8 %. However, the thesis claims that increased costs may be acceptable as these concepts will reduce the need for investments in cross-national infrastructure.

The most cost-effective concepts for increasing the wind-friendliness of existing distributed generators relies on installing a relatively small heat pump, limiting the electric capacity of the heat pump to no more than 10 % of the electricity generating capacity of the distributed generator. The most cost-effective heat pump concepts are more cost-effective than concepts for integrating an electric boiler.

The thesis provides new metrics, like the relocation coefficient, for evaluating the wind-friendliness of distributed generators, and the cost-effectiveness hereof, and offers a new interactive modelling framework that allows for researchers and local operators to interact on evaluating options for domestic integration with respect to energy, environmental, and economic consequences.

Keywords: sustainable energy system design, intermittency, large-scale heat pumps, distributed cogeneration, cold storage, relocation, domestic integration of wind power, interactive techno-economic modelling software.